Mud Weight Evaluation Based on Safe Mud Window in Drilling Well “X-1” to Overcome Caving and Partial Loss Problems in The Oil Field

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Abstract. Drilling of Well X-1 in the North Sumatra Basin at a depth of 2887-3186 m TVD occurred partial loss, and caving at a depth of 500-1650 m TVD. To overcome this problem, it is necessary to use the safe mud window concept. Drilling mud density planning must be greater than the pore pressure and shear failure gradient but not more than the minimum horizontal stress and fracture pressure. The purpose of this paper is to make an accurate subsurface pressure analysis and to overcome problems caused by the mud weight planning errors used based on the safe mud window, and can be used as a reference for further drilling of wells that have field conditions and stratigraphy such as the Well X-1. In conducting safe mud window analysis, there are several parameters that need to be estimated in order to make a safe mud window, namely formation pressure, formation fracture pressure, minimum horizontal stress, maximum horizontal stress, vertical stress / overburden pressure, and shear failure gradient. From the results of the safe mud window on Well X-1, the actual mud weight data used during drilling is entered. After being analyzed, at a depth of 500-1050 m TVD caving occurs because the density value used is smaller than the shear failure gradient, while at a depth of 1050-1600 m there is kaolinite mineral which causes caving. At a depth of 2829-3281 m TVD the density value is greater than minimum horizontal stress (SHmin). Here, caving occurs if the density value used is smaller than shear failure gradient and partial loss occurs if the density used is greater than SHmin. Based on the safe mud window, the optimal mud weight for drilling at a depth of 36-354.2 meter on a 20” route is 9.2-9.4 ppg. At a depth of 354.2-948 meter on a 16” route is 14.49-15.33ppg. At a depth of 948-1619 meter on a 13 3/8” route is 15.45-17.65ppg. At a depth of 1619-2829 meter on a 9 5/8” route is 17.36-17.76ppg. At a depth of 2829-3281 meter on a 7” route is 16.57-16.7ppg. And at a depth of 3281-3796.1 meter is 13.49-13.74ppg in order to avoid partial loss and caving problems.

Keywords : Drilling, Mud Weight, Safe Mud Window, Caving, Partial Loss

1. Introduction

Well X-1 is an exploration well with drilling targets in the shale rock reservoir in the Belumai Formation which is a gas reservoir. Well X-1 is located in the North Sumatra basin, precisely in the Aru area. It is well known that the North Sumatra Basin fault type is a "strike-slip" type [7]. In that area there is also a clay diagenesis process which results in overpressure [7]. In the Well X-1 drilling of 2887-3186 m TVD depth, partial loss and caving occurred
at a depth of 500-1650m TVD. This indicates that the drilling at Well X-1 uses a mud density design based on the pressure window.

Partial loss and caving problems usually occur during drilling operations. Partial loss is a form of lost circulation, which is an occurrence of loss of drilling fluid into the formation due to differences in pressure during drilling operations. The effect of lost circulation itself, apart from the extended drilling time, also causes damage to oil and gas formations and of course economic losses [5]. Partial loss is specifically the loss of a portion of the drilling mud into the formation. The drilling mud that enters the formation when partial loss occurs is estimated at 10-100 bbl/day [4]. The caving problem is related to shale formation. Caving occurs because the formation is not compact so the formation will collapse. The shale formation will be reactive to the drilling fluid, especially water, so it will cause the formation to be not compact [8]. To overcome this problem, a mud density design based on a safe mud window is required.

To design a safe mud window, log data such as Gamma Ray Log, Density Log, Resistivity Log and Sonic Log are required. Formation pressure data obtained from DST, fracture pressure data from the Leak of Test (LOT). Furthermore, the overpressure mechanism is selected to determine what method will be used when calculating the formation pressure, then calculating the overburden stress, formation pressure, formation fracture pressure, minimum horizontal stress, maximum horizontal stress, and shear failure gradient. The range between the shear failure gradient and the minimum horizontal stress is the safe mud window, the results of the safe mud window can be used for planning mud density in further well drilling if it has stratigraphic conditions close to Well X-1 [6,7].

2. Methodology
In conducting geopressure analysis, there are several parameters that need to be estimated for making safe mud windows, namely formation pressure, formation fracture pressure, minimum horizontal stress (SHmin), maximum horizontal stress (SHmax), vertical stress / overburden pressure, and shear failure gradient (SFG). The first step is to collect log data and regional geological data that are in Well X-1. The log data required includes Gamma Ray Log, Density Log, and Sonic Log. Geological data required is well lithology and dominant fault types that affect the value of the tectonic factor that applies around the Well X-1 area. In analyzing the subsurface pressure profile, Drillworks Predict is used to facilitate the calculation of the subsurface pressure profile.

The steps in analyzing the subsurface pressure profile are evaluating the shale line on the gamma ray log, the value obtained from this gamma ray log is that if it exceeds the shale line, it includes the shale zone and if it is less than the shale line it is a nonshale zone. Next is to determine the overburden pressure using bulk density data from the density log. Then analyze the normal compaction trend on the sonic log and the resistivity log. Then analyze the overpressure mechanism that occurs in the Well X-1 by plotting the sonic log and density log vs depth, whether the mechanism that occurs in the Well X-1 is the loading mechanism or the unloading mechanism. The next step is to calculate pore pressure using the Eaton Method, Bower’s Method and Equivalent Depth Method in accordance with the overpressure generating mechanism [2,3]. This calculation uses the transit time interval data from the sonic log. The calculation of each method will be compared with each other and correlated with the actual problem.
that occurs. In addition, Eaton Method and Bower's Method have an exponential component to the equation where the value can vary in each field. This exponential amount will be calibrated with actual pore pressure data which can be obtained from several data, including from DST data, RFT and pore pressure when the kick occurs. After getting the pore pressure, the next thing to do is to calculate the fracture pressure using the Hubbert & Willis, Matthews & Kelly and Eaton equations [3,9]. Previously, we had to determine the Poisson ratio with various methods, namely the Brocher method, the Ludwig method and the Zoback & Castagna method [9]. After getting the poisson ratio value, the next step is to calculate the fracture pressure according to the Well X-1 calibrated using the LOT data.

After analyzing the subsurface pressure profile, a pressure window is obtained from the analyzed well, which then adds the shear failure gradient and minimum insitu stress parameters to obtain a safe mud window. The calculation of the shear failure gradient is obtained using the transite time interval data from the sonic log. In addition, the maximum & minimum horizontal stress parameters are required in the calculation of the shear failure gradient. In the safe mud window criteria, the density of the sludge used must be greater than the value of the shear failure gradient / collapse pressure and must not be greater than the minimum value for insitu stress.

3. Results and Discussion

Geopressure analysis is used to determine the causes of problems that occur in the Well X-1. Afterwards, evaluation about the source of problems was carried out based on the safe pressure window in order to prevent the occurrence of the same problem in the Well X-1 for drilling at locations around the wells or wells that had appropriate lithology.

3.1 Geopressure Analysis Using Drillworks Software

Several steps are needed to conduct geopressure analysis. It start from data input to determining the value of the shear failure gradient. This geopressure analysis can be done using Drillworks Software.

3.1.1 Log Data Input

At this stage, log data input such as gamma ray log, sonic log, and density log are carried out. The inputted log must be the log data at True Vertical Depth (TVD) so that the process is more accurate, and in accordance with actual conditions.

![Figure 2. The Result of Log Data Input (Gamma Ray Log, Sonic Log, and Density Log)](image)

3.1.2 Shale Line Analysis

At this stage the shale and nonshale zones are separated. For this separation, the shale line is drawn so that the shale and nonshale zones can be separated. If the gamma ray log value is to the left of the shale line, the area is
nonshale, but if it is to the right of the shale line, the area is a shale zone. This analysis is used to then analyze the type of overpressure that occurs in the Well X-1 drilling based on the response from sonic data that has shale lithology. You can see the effect of shale line drawing, shown by the SHPT DT chart display. The chart shows depth data where the formation is a shale formation.

![Figure 3. Evaluation Results of Shale Line on Gamma Ray Log](image)

3.1.3 Determination of the Type of Overpressure Mechanism

Loading and Unloading are components that cause overpressure in rock formations. Loading is an overpressure where the value of effective stress is constant. Meanwhile, Unloading is an overpressure where if the value of the effective stress gets deeper into the depth of the formation, the smaller it will be. [6]. To determine the type of overpressure mechanism that occurs, it can be seen from the graph of the log readings, as well as the porosity value [6,7]. There are 2 graphs, namely Depth vs Transit time, and Depth vs Density. Both charts are analyzed to determine the cause of the overpressure, whether it includes the loading mechanism or the unloading mechanism. From the graphic results obtained, it can be concluded that the mechanism for overpressure formation in the Well X-1 is the loading mechanism and the unloading mechanism.

![Figure 4. Depth vs DT, and Depth vs Density plot results](image)
3.1.4 Determination of Overburden Gradient

It is necessary to calculate the overburden pressure (OBP) because this parameter is always used for calculations at the next stage, where the calculation of pore pressure, fracture pressure, SHmin, SHmax, and shear failure gradient uses this parameter. For the calculation of overburden pressure requires density data for each depth, while the available density data is limited, to interpret rock density at depths where there is no log data, the Gardner equation is used to have results calibrated with density log data so that the density data is combined using Gardner and data of density log, which produces RHOB Composite which represents log data in each depth and this data can be used as bulk density in the overburden gradient (OBG) calculation process [1].

![Figure 5. Results of Overburden Gradient in Drillworks Software](image)

The results of manual overburden pressure calculations are presented in Table 1. Where the value of the overburden pressure calculation results increases with increasing depth.

| TVD (meter) | TVD (ft) | Density (gr/cc) | OBG (Psi) | OBG (ppg) |
|-------------|----------|----------------|-----------|-----------|
| 500         | 1640.5   | 2.542          | 1806.34   | 21.175    |
| 1000        | 3281     | 2.457          | 3491.88   | 20.467    |
| 1500        | 4921.5   | 2.437          | 5195.19   | 20.300    |
| 2000        | 6562     | 2.447          | 6955.34   | 20.384    |
| 2500        | 8202.5   | 2.448          | 8697.73   | 20.392    |
| 3000        | 9843     | 2.451          | 10450.1   | 20.417    |
| 3500        | 11483.5  | 2.477          | 12321.1   | 20.633    |

3.1.5 Determination of Pore Pressure

To determine the pore pressure, it must match the pressure data of Well X-1, which is 16 ppg (maximum pressure in the overpressure zone). The method used in calculating pore pressure is Eaton and Bowers. Both have results that match the pressure data [2,3]. To calibrate the results, it is necessary to look at the actual Mud Weight (Mwactual) data used. The actual MW and calculation of the pore pressure method can be seen in Table 2. The
calculation value that is below the actual MW is the value that is sought, because the drilling of the Well X-1 does not occur kick.

**Table 2. Pore Pressure Results Using Eaton and Bowers Methods**

| Depth (meter) | Pore Pressure (ppg) |
|---------------|---------------------|
|               | MW              | Eaton | Bowers |
| 1000          | 11.662          | 10.91 | 11.89  |

In **Figure 6**, the graph of the calculation of pore pressure using the Eaton method.

![Figure 6. Pore Pressure Results Using Eaton Methods](image)

The results of manual pore pressure calculation are presented in **Table 3**, where the pore pressure calculation results are influenced by the value of overburden pressure and NCT.

**Table 3. Results of Manual Pore Pressure Calculation with the Eaton Method**

| TVD (m) | DT (us/ft) | NCT (us/ft) | OBG (ppg) | PP Eaton (ppg) |
|---------|------------|-------------|-----------|---------------|
| 500     | 163.123    | 163.123     | 21.1749   | 8.330         |
| 1000    | 151.288    | 141.912     | 20.4668   | 10.450        |
| 1500    | 140.56     | 127.17      | 20.3002   | 11.435        |
| 2000    | 131.2      | 115.785     | 20.3835   | 12.099        |
| 2500    | 132.867    | 106.734     | 20.3918   | 14.139        |
| 3000    | 138.885    | 99.485      | 20.4168   | 15.974        |
| 3500    | 94.104     | 92.752      | 20.6334   | 8.853         |

3.1.6 Determination of Fracture Pressure

After calculating rock mechanics using several methods, the next step is to calculate the fracture pressure. In calculating fracture pressure, several methods are used, namely Eaton, Mathews & Kelly, and Hubbert & Willis.
From some of these equations, the results are compared, for the closest results to the LOT data is the method to be used in calculating the fracture pressure at Well X-1. As shown in \textbf{Figure 7}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fracture_pressure.png}
\caption{Results of the Fracture Pressure LOT Validation with Several Methods}
\end{figure}

The method used is Mathews & Kelly because the results of the calculations match the LOT. Then this equation is the one used in calculating the fracture gradient. The Mathews & Kelly method calculates 2 subsurface pressures, namely pore pressure and overburden gradient. There is one more parameter, k which is the effective stress ratio, which is the ratio of effective stress to fracture pressure and effective stress to overburden pressure.
Figure 8. Fracture Pressure Results with the Mathews & Kelly Method

The results of manual fracture pressure calculation are presented in Table 4. Where the value of the fracture pressure calculation is influenced by the value of overburden pressure and pore pressure.

Table 4. The Result of Manual Fracture Pressure Calculation by Mathews & Kelly Method

| TVD (m) | PP Eaton (ppg) | k   | OBG (ppg) | FG (ppg) |
|--------|---------------|-----|-----------|----------|
| 500    | 8.333         | 0.751| 21.1749   | 17.976   |
| 1000   | 9.386         | 0.75 | 20.4668   | 17.697   |
| 1500   | 10.973        | 0.892| 20.3002   | 19.293   |
| 2000   | 12.099        | 0.913| 20.3835   | 19.663   |
| 2500   | 14.139        | 0.886| 20.3918   | 19.679   |
| 3000   | 15.974        | 0.837| 20.4168   | 19.693   |
| 3500   | 8.852         | 0.74 | 20.6334   | 17.570   |

3.1.7 Determination of Minimum and Maximum Horizontal Stress

After calculating the fracture pressure, the next step is to determine the minimum horizontal stress and maximum horizontal stress. To determine the minimum horizontal stress and maximum horizontal stress, it is necessary to know the type of fault that occurs in the North Sumatra Basin, the type of fault in the North Sumatra Basin is a strike-slip, so the value of Maximum Horizontal Stress is greater than Vertical Stress and Vertical Stress is greater than Minimum Horizontal Stress (Shmax > Sv > Shmin). Based on the type of strike-slip fault the calculation results in Figure 9. show that it is true that the North Sumatra Basin is a strike-slip fault because the value of Shmax > Sv > SHmin. The minimum horizontal stress and maximum horizontal stress parameters are very important for the calculation of the next parameter, namely the shear failure gradient.
Figure 9. Results of SHMin Using Mohr-Coloumb Friction Method and SHMax Using Anderson Method

The results of the manual calculation of the minimum horizontal stress are presented in Table 5. Where the value of the SHmin calculation is influenced by the value of overburden pressure, pore pressure, and empirical number.

Table 5. Minimum Horizontal Stress Calculation Results Using Mohr-Coulomb Friction Method

| TVD (m) | FA (deg) | OBG (ppg) | PP (ppg) | Shmin (ppg) |
|---------|----------|-----------|----------|-------------|
| 500     | 22.304   | 21.1749   | 8.33     | 16.789      |
| 1000    | 19.394   | 20.4668   | 10.4496  | 17.655      |
| 1500    | 24.787   | 20.3002   | 11.4354  | 17.081      |
| 2000    | 22.157   | 20.3835   | 12.099   | 17.777      |
| 2500    | 22.732   | 20.3918   | 14.1391  | 18.515      |
| 3000    | 21.455   | 20.4168   | 15.9744  | 19.356      |
| 3500    | 32.465   | 20.6334   | 8.85271  | 14.739      |

The results of manual calculation of maximum horizontal stress are presented in Table 6. Where the value of the fracture pressure calculation is influenced by the value of overburden pressure, SHmin, and tectonic factor.
Table 6. Result of Manual Maximum Horizontal Stress Calculation Using Anderson Method

| TVD (m) | k (dimensionless) | Shmin (ppg) | OBG (ppg) | Shmax (ppg) |
|---------|-------------------|-------------|-----------|-------------|
| 500     | 1.2               | 16.789      | 21.1749   | 22.052      |
| 1000    | 1.2               | 17.6547     | 20.4668   | 21.029      |
| 1500    | 1.2               | 17.0812     | 20.3002   | 20.944      |
| 2000    | 1.2               | 17.7768     | 20.3835   | 20.905      |
| 2500    | 1.2               | 18.5149     | 20.3918   | 20.767      |
| 3000    | 1.2               | 19.3557     | 20.4168   | 20.629      |
| 3500    | 1.2               | 14.739      | 20.6334   | 21.812      |

3.1.8 Determination of Shear Failure Gradient (SFG)

The next step is to determine the Shear Failure Gradient value. The method used is Modified Lade Criteration because this method takes into account 3 principal stresses, namely minimum horizontal stress, overburden stress, and maximum horizontal stress [9]. In addition, this method also takes into account 2 geomechanical parameters, namely fraction angle and cohesive strength.

Figure 10. Shear Failure Gradient Results Using the Modified Lade Method

Determining the Shear Failure Gradient using the modified lade method has the advantage that this method can be done in all areas, and takes into account the three stress principles that have been carried out in the previous calculations, namely overburden pressure, minimum horizontal stress and maximum horizontal stress.
3.2 Evaluation of the Use of Mud Weight during Drilling and Problems that Occur in the Well X-1

At this stage, an evaluation of the use of mud weight is carried out whether it is in accordance with the safe mud window, and identifies the causes of the problems that occur in the Well X-1 drilling. If the mud weight design is not in accordance with the safe mud window, there will be drilling problems such as caving and partial loss. Problems that occur during drilling operations can be seen in Table 7.

Table 7. Problems at the Well X-1

| Problem    | Depth (m TVD) | Formation               | Lithology                      |
|------------|--------------|-------------------------|--------------------------------|
| Caving     | 500-1050     | Keutapang-Top Middle Baong | Shale, Sandstone, Limestone   |
| Caving     | 1050-1650    | Middle Baong - Gebang   | Shale, Sandstone, Limestone   |
| Partial loss | 2877.35     | Top Gebang              | Shale                          |
| Partial loss | 2932.277     | Lower Baong             | Shale                          |
| Partial loss | 3181.927     | Lower Baong             | Shale                          |

The mud weight used during the drilling operation is not in accordance with the safe mud window, resulting in partial loss and caving problems.

Figure 11. Mud Weight Used When Drilling in Well X-1

Based on the safe mud window that has been made at a depth of 500-1050m TVD, caving occurs because the value of the mud weight used is smaller than the shear failure gradient so that caving occurs, at a depth of 2887, 2945, and 3186 mMD, it can be seen that the actual mud weight is above the minimum horizontal stress. This indicates that the weight of the mud used exceeds the minimum horizontal stress in the formation resulting in partial loss. In accordance with the conditions that occurred in Well X-1, where at a depth of 2887, 2945, and 3186 mMD, there was a partial loss problem. The value of the mud weight used during drilling operations can be seen in Table 8.
Table 8. Mud Weight Actual Drilling in Well X-1

| Depth (m) | Traject (inch) | Densitas (ppg) |
|-----------|----------------|----------------|
| 0-36      | 30             | -              |
| 36-354.2  | 20             | 9.2 – 9.4      |
| 354.2-948 | 16             | 9.99 – 11.66   |
| 948-1619  | 13 3/8         | 15.8 – 16.66   |
| 1619-2829 | 9 5/8          | 17.49 – 18.49  |
| 2829-3281 | 7              | 17.07 – 18.24  |
| 3281-3800 |                | 13.49-13.74    |

3.3 Optimum Mud Weight Design In Well X-1

To solve the problems that occur, it is necessary to evaluate the mud weight used, namely the value of the mud weight must be greater than the shear failure gradient, and smaller than the minimum horizontal stress, so that caving and partial loss do not occur. For Mud Weight planning with the safe mud window approach, it is expected to minimize the occurrence of problems in the well. The recommended use of Mud Weight can be seen in Figure 12.

![Figure 12. Safe Mud Window and Mud Weight Recommended in Well X-1](image-url)
After obtaining the safe mud window value, the optimum mud weight design can be carried out, which is between the shear failure gradient and the minimum horizontal stress. Before doing this, the actual mud weight plot must be carried out with the safe mud window. The use of mud weight on Well X-1 is more than the minimum horizontal stress, and less than the shear failure gradient. This resulted in the drilling of Well X-1 occurring with caving problems and partial loss. By modeling the safe mud window, it can be used as a reference for the optimum density design for drilling wells around Well X-1 so that similar problems do not occur.

On routes 16” and 13 3/8”, with a depth of 500-1050 m TVD, the mud weight used is 9.99-11.66 ppg on the 16” route, and 15.8-16.66 ppg on the 13 3/8” route, the density on these routes is smaller than SFG so there is a caving problem. From the analysis, it was found that the mud weight used was 14.49-15.33 ppg on the 16” route, and 15.45-17.65 ppg on the 13 3/8” route. At a depth of 1050-1650 m, caving occurs but the mud weight value is greater than SFG, caving at that depth is due to drilling through the weak formation. On route 9 5/8 “ and route 7”, the depth of 1619-2829 m TVD and 2829-3281 m TVD mud weight used is 17.49-18.49 ppg, and 17.07-18.24 ppg. The density of the mud used is not correct if it is adjusted to the existing subsurface pressure because the mud weight value is greater than the minimum horizontal stress. So that there is a partial loss problem. From the results of the analysis at this depth interval, the weight of mud that should be used during the drilling process is 17.36-17.76 ppg on route 9 5/8 “, and 16.57-16.77ppg on route 7”.

Based on the safe mud window, the optimum mud weight for drilling is at a depth of 36-354.2 meter on a 20” route is 9.2-9.4 ppg. At a depth of 354.2-948 meter on a 16” route is 14.49-15.33 ppg. At a depth of 948-1619 meter on a 13 3/8” route is 15.45-17.65 ppg. At a depth of 1619-2829 meter on a 9 5/8” route is 17.36-17.76 ppg. At a depth of 2829-3281 meter on a 7” route is 16.57-16.77 ppg. And at a depth of 3281-3796.1 meter is 13.49-13.74 ppg. In order to avoid partial loss and caving problems. The results of the analysis that has been carried out can be used as a reference for further drilling in the vicinity of the Well X-1. The range of results of the evaluation of mud weight is the limit of static mud weight and dynamic mud weight, where the static mud weight value is not smaller than the lowest recommended mud weight value and dynamic mud weight is not higher than the highest recommended mud weight.

4. Conclusion

The conclusions of this paper are explained below.

1. Overpressure that occurs in the Well X-1 is loading and unloading due to a failure of compaction and fluid-expansion caused by the diagenetic clay.
2. In Section 1 there is a caving problem that occurs at a depth of 500-1050m (routes 16” and 13 3/8”) due to dynamic mud weight actual is smaller than SFG, to solve this problem must change the mud weight on route 16” to 14.49-15.33 ppg, and the route 13 3/8” to 15.45-17.65 ppg.
3. In Section 2 (1050-1650 m depth) a caving problem occurs but the actual dynamic mud weight condition is greater than SFG. Caving in this section occurs due to drilling through an incompatible formation.

| Depth (m) | Traject (inch) | Density (ppg) |
|-----------|----------------|---------------|
| 0-36      | 30             | -             |
| 36-354.2  | 20             | 9.2 – 9.4     |
| 354.2-948 | 16             | 14.49-15.33   |
| 948-1619  | 13 3/8         | 15.45-17.65   |
| 1619-2829 | 9 5/8          | 17.36-17.76   |
| 2829-3281 | 7              | 16.57-16.7    |
| 3281-3796.1|               | 13.49-13.74   |
4. In Sections 3, 4, and 5, partial loss occurs because the dynamic mud weight actual value is greater than the Shmin value which results in fracture formation and partial loss, to overcome this problem you must change the mud weight on route 9 5/8" to 17.36 -17.76 ppg, and the route 7" to 16.57-16.7 ppg.

5. The range of results of the evaluation of mud weight is the limit of static and dynamic mud weight, where the static mud weight value is not smaller than the lowest recommended mud weight value and the dynamic mud weight is not higher than the highest recommended mud weight.

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