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Limiting Drilling Parameters to Control Mud Losses in the Shuaiba Formation, South Rumaila Field, Iraq

Abo Taleb T. Al-Hameedi, Shari Dunn-Norman, Husam H. Alkinani, Ralph E. Flori, and Steven A. Hilgedick, Missouri University of Science and Technology

Abstract

Fluid losses during drilling lead to greater expenses from mud loss, difficulty in well control and zonal isolation, and NPT. The purpose of this paper is to predict allowable operational ranges for drilling parameters to limit mud loss volume in the Shuaiba formation in the South Rumalia Field in Iraq, in which these events are common. Mud loss data from more than 50 wells were compiled from daily drilling reports, final well reports, and technical reports. Key drilling parameters were analyzed using statistical and sensitivity analysis to better understand the relationship between the amount of losses and various drilling parameters, to provide a guide to the mitigation or avoidance of mud losses.

From this analysis a model was developed to predict mud losses in the Shuaiba formation. Observations that have been made from the amount of the loss model are ECD, MW, and Yp have a significant impact on the amount of the loss model; however, SPM, RPM, and ROP have a minor effect on the amount of the loss model. An equivalent circulation density model is developed to estimate ECD in the Shuaiba formation, and from this model it is deduced that MW, ROP, and Q have a significant impact on ECD respectively. Nevertheless, RPM and Yp have a minor impact on the ECD. A rate of penetration model is developed to estimate ROP in the Shuaiba formation. It is concluded that WOB, RPM, and SPM have a significant impact on the ROP respectively, but mud MW, ECD, and Yp have a minor influence on the ROP. Due to the lack of published studies about the Shuaiba formation, this work can serve as a useful resource for this formation, and provide a method for predicting mud loss volumes, then limiting operational parameters to mitigate such losses in future wells in fields with similar lithology.

Introduction

Mud losses or lost returns is the partial, severe, or total loss of circulating drilling mud from the annulus to the thief formation. It presents the partial or complete loss of drilling fluid, not simply filtrate to the formation. Mud losses can result from either natural or induced causes and can range from a couple of barrels per hour to hundreds of barrels in minutes. Mud loss is one of drilling's biggest expenses in terms of rig time and safety. While drilling may be managed with partial Losses, uncontrolled mud losses can result in a hazardous pressure control situation and loss of the drilling operations. Mud loss is a significant problem in the oil and gas industry and has been shown to be one of the top contributors to non-productive rig time.[1] By industry estimates, more than 2 billion USD is spent on managing and mitigating this problem.[2] Although it may occur in any formation, some primary contributors to loss circulation are high permeability weakly consolidated formations, fracture calcium carbonate reservoirs and depleted aquifer formations.[3]

Mud losses may also occur at any point in the drilling operation. If losses occur while drilling a long section of the well, the objective of the treatment will likely be to plug off or limit the losses to allow drilling ahead without casing and cementing. In other situations, the approach may be to limit the losses and cement the well. Given sufficient experience in drilling a particular type of formation, it may be possible to avoid, or significantly minimize mud losses events by controlling mud properties, drilling rate, or other field parameters. However, this requires a high level of drilling experience in an area, which is generally not available. For this reason, the industry relies heavily on using methods of mitigating mud losses events after they occur.

This paper provides basic information on mud losses, including an introduction to the problem, identification of the major factors that affect mud losses. The study summarizes mud loss information extracted from drilling data from the South Rumalia Field in Iraq. Mud losses screening criterion are presented for the Shuaiba formation, based on the historical mud loss, three mathematical models for mitigation, and integration of these three models to identify potential solutions.

Introduction to the South Rumaila Field

The Rumaila Field is a super-giant oil field located near Basra city in southern Iraq, and approximately 20 mi (32 km) from the Kuwait border shown in Figure 1.[4] The Basra Petroleum Company (BPC), an associate company of the Iraq

Petroleum Company (IPC), discovered this field in 1953. The Rumaila Field is considered the third largest field in the world. Currently the field is owned by Iraq and subcontracted to BP and China National Petroleum Corporation (CNPC) under Iraq Producing Field Technical Service Contract (PFTSC). BP is an operator of the project with 47.6% while CNPC and State Oil Marketing Organization (SOMO) hold 46.4% and 6%, respectively. As of October 2016, the field produces 1,000,000 barrels per day. From approximately 200 production wells.

Table 1[4] provides an overview of the lithology and producing formations in the South Rumaila Field. Prior to 2010, the field was under supervision of the South Oil Company, and the primary formation for development was Zubair formation. As of 2010, British Petroleum became the operator for this field, and development focus shifted to the Mishrf.

Figure 1. South Rumaila Field (South Oil Company, 2016 [4])

Table 1. Lithology of the South Rumaila Field (South Oil Company, 2011[4])

Formation	Description	Formation Intervals	Problems
DIBDIBA	Sand & Pebble	200 m or less	High gel strength, sand content, and filtration.
L. FARS	Argillaceous Limestone	200 - 315 m	High viscosity and balling.
GHAR	Sand & Pebble	315 - 440 m	Wash pipe and corrosion
DAMMAM	Dolomite	440 -700 m	Lost Circulation.
RUS	Anhydrite	690 – 860 m	High contamination of Ca^{++}.
UMM ER-RADHUMA	Dolomite	860 – 1310 m	H_2S flow.
TAYARAT	Shale	1300 – 1550 m	H_2S flow.
SHIRANISH	Argillaceous Limestone	1550 – 1660 m	Stuck pipe and low penetration rate.
HARTHA	Limestone	1660 – 1850 m	Lost Circulation.
SADI	Limestone	1850 – 2150 m	Kick due to high pressure.
TANUMA	Shale	2150 – 2200 m	Shale sloughing and collapse.
KHASIB	Limestone	2200 – 2250 m	Formation hardness is high.
MISHRIF	Limestone	2240 – 2390 m	Blowout due to abnormal pressure.
RUMAILA	Limestone	2400 – 2490 m	Low penetration rate.
AHMADI	Shale	2490 – 2635 m	Shale sloughing and collapse.
MAUDDUD	Limestone	2630 – 2723 m	Partial mud losses.
NAHR UMR	Shale	2720 – 2990 m	Shale collapse and stuck pipe.
SHUAIBA	Limestone	2990 – 3090 m	Lost circulation due to fractures and low penetration rate.
U. SHALE ZUBAIR	Shale	3090 – 3205 m	Shale collapse and stuck pipe.
U. SANDSTONE ZUBAIR	Sandstone	3205 – 3390 m	Low penetration rate.
M. SHALE ZUBAIR	Shale	3390 – 3445 m	Shale collapse and stuck pipe.
L. SANDSTONE ZUBAIR	Sandstone	3445 – 3515 m	Low penetration rate.

Table 1. Lithology of the South Rumaila Field (Cont'd) (South Oil Company, 2011[4])

The South Rumaila field is estimated to have about 17 billion barrels, which is equivalent to 12% of Iraq's oil reserves. One of the greatest challenges in drilling wells in the South Rumaila Field is the amount of non-productive time (NPT) caused by mud losses. These mud losses represent more than 66% of the total non-productive time. More than 90% of wells that have already been drilled have suffered from mud loss problems [2,4]. Figure 2 shows a typical wellbore schematic with all the drilled hole sections and casings in place.

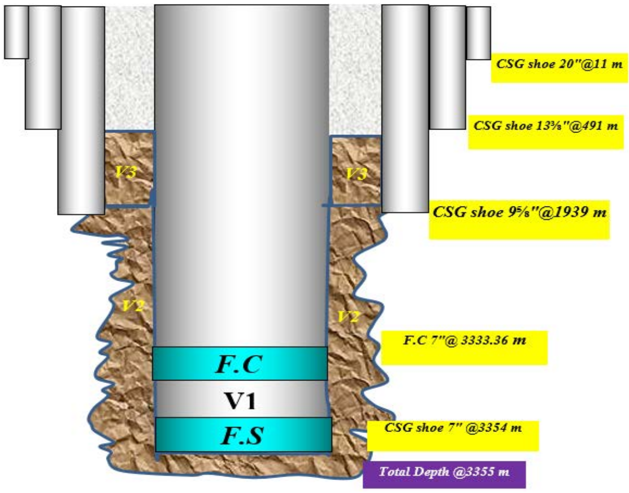

Figure 2. Wellbore Schematics with all the Open Hole Sections and Casings in Place

Shuaiba Formation

The Shuaiba formation occurs at approximately 2900 m and is a limestone with little to no visible porosity. However, the formation is highly susceptible to fracturing and mud losses, which is more troublesome and even more complicated than mud losses in the other formations highlighted in Table 2. Sometimes, mud losses in the Shuaiba formation lead to abandonment of the drilling operation due to unsustainable non-productive time (NPT) and drilling cost. Table 2 summarizes the unwanted consequences due to mud losses in the Shuaiba formation.

Table 2. Summary of Unwanted Consequences of the Mud Losses

Problem	Description
Financial Impact	Loss volumes of the mud while drilling lead to a remarkable financial impact on the drilling operations cost.
Formation Damage	Large mud losses have a negative impact on the productive formations because mud losses will damage formation after invasion them.
NPT	Non-productive time.
Kick	Kicks or blowouts issues due to mud level reduction in the wellbore especially in front of abnormally high formations pressures.
Borehole Enlargement	Borehole enlargement occurs due to the drilling mud losses.
Pipe Sticking	Inefficient hole cleaning lead to mechanical stuck pipe due to lost circulation.
Bit Damage	Mud losses cause reduction of the bit life due to ineffective lubrication.

It is vital to drilling success that the supervisor, mud engineer, log engineer, and geologist make preparations before drilling this formation in order to take all the necessary precautions. Current field methods used to drill the Shuaiba formation include reduction of WOB, RPM, SPM; adjusting mud properties; slow and careful removal or insertion of drill pipe to avoid surging, and breaking gel strength with rotation.[4] Rig and field personnel conduct extensive planning prior to drilling the Shuaiba because of the extreme risks associated with mud loss. Increased supplies of mud losses materials are ensured, and there is precise monitoring of all drilling parameters and measurements, the shale shaker, desilter, degasser and mud-cleaners. These precautions are based on field experience.

Figure 3 shows the borehole and well construction typical of a well drilled in the South Rumaila Field at the time the well passes through the Shuaiba formation. Both the 13-3/8” and 9-5/8” casing strings have been set. Commonly an 8 $^{1/2}$” bit is used to drill through the formation.

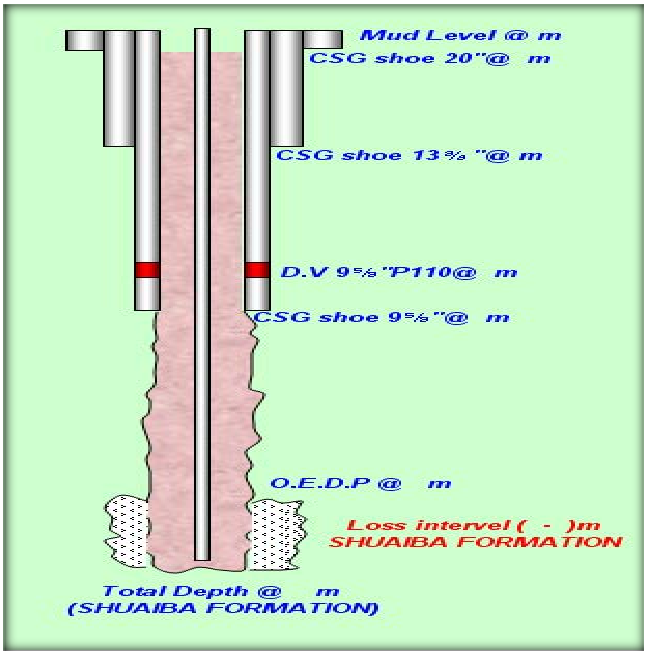

Figure 3. Lost Circulation Mud in Shuaiba Formation

Factors Impacting Mud Losses

There are multiple factors that lead to mud losses in the Shuaiba formation. Below are the major factors that cause this issue[1, 4]:

Lithology

The lithology for the Shuaiba formation is limestone. The attributes of this limestone is mudstone to wackstone, very pale orange to moderate greenish yellow, moderately hard, fine crystalline, blocky, earthy, luster, compact, commonly pyritic, no visible porosity, no oil show. Limestone will be weak and prone to induced fracture which causes mud loss.

High Mud Weight

Mud pressure is the major cause of mud losses in the Shuaiba formation. High fluid density will aggravate mud losses. High mud weight typically leads to more severe types of mud loss. Therefore, it is very important to design an optimum mud weight, and it is prudent to precisely monitor drilling mud density during drilling this formation in order to maintain the desired mud weight.

High Yield Point (Yp)

This parameter a major cause of mud loss. By increasing yield point (Yp), the mud circulating pressure will increase which in turn cause extra pressure on the formation. In addition, a high mud yield point creates related high Equivalent Circulation Density (ECD) in the annulus, which in turn will cause high friction and high losses pressure in the annulus. Therefore, it is crucial to control yield point within allowed limits.

High Pump Pressure (High SPM)

Increasing pump rate increases pressure on the formations. Therefore, it is common practice to limit SPM to avoid extra pressure on the formation.

High RPM

Increased RPM causes an increase in ECD, so RPM indirectly affects mud losses. The effect of RPM on ECD is greatest when resuming drilling operations after shut down. This is also due to the increased Yp of the drilling fluid. High rotation for drilling string will directly or indirectly lead to more pressure on the formation.

High Filtrate Rate

Increased measured mud cake directly affects ECD as it impedes drilling fluid flow and indicates increased plastic viscosity, which is also directly proportional to ECD. Hence a high filtrate rate indirectly affects mud losses. High filtration will also cause bridging in the annulus which in turn may narrow and seal the annulus.

The Gel Strength

The gel strength of the drilling fluid increases with time when circulation is stopped. Due to gel strength of the fluid, an increase in pressure on the formation occurs in the transition between static and dynamic conditions when resuming drilling operations after a shut down. Therefore, gel strength of the mud indirectly affects mud losses.

High Jet Force

Higher jet velocity as a result of bit nozzle selection increase pressure on the formation at the bit indirectly affecting mud losses. In formations where mud losses are of concern, such as the Shuaiba formation, it is preferable to use bit without nozzles to avoid jet velocity and easily do required treatment.

Classifications of Mud Losses

Mud losses events are categorized according to the total volume of fluid lost during the event. The volume of mud losses depends on a number of factors, including formation properties, drilling fluid properties, and formation breakdown pressure [5]. The categories of losses are described as seepage, partial, severe or complete losses, depending on the volumes of mud losses and thief formation [6]. All of the mud losses for wells in the Shuaiba field are reported according to this classification system.

Seepage loss

These are small losses that could occur in any formation due to differential pressure (over-balanced drilling). The other name for this type of loss is filtration. The fluid loss rate is classified as 0.5–1 m^3/hrs (3-6 bbls/hrs).

Partial Loss

This kind of mud loss usually happens in gravel beds, small natural horizontal fractures and barely opened induced vertical fractures. Partial fluid loss rate is classified as 1-10 m^3/hrs (7-70 bbls/hrs).

Severe Loss

This kind of mud loss will be more than partial loss. Severe mud loss is typically 15 or more m3/hrs (95 or above bbls/hrs).

Complete Loss

Complete mud loss means there will be little to no returns to surface. This type of loss happens in long open sections of gravel, large natural horizontal fractures, caverns, interconnected vugs and to widely open induced fractures.

Methodology

Given the number of drilling parameters that affect mud loss and the complex interrelationship between some of the drilling parameters, a drilling engineer is challenged to select the optimum value for each one. The purpose of this work was to develop a more systematic approach to determining the best values for these parameters while drilling the Shuaiba formation. The methodology developed is based on analyzing actual mud loss events while drilling the Shuaiba formation, to develop key statistical models for ROP, ECD, and mud losses. These models are then tested with other Shuaiba well data to check their validity and to demonstrate how the models can be used to set key drilling parameters.

Mud loss events for more than 50 wells drilled in the South Rumaila Field were identified through reading and summarizing daily drilling reports (DDR), final well reports, and technical report. Critical drilling parameters such as MW, ECD, Yp, ROP, SPM, RPM, and bit nozzles were recorded at the time of each mud loss event. The severity of the mud loss event, depth and result of any mitigation attempts were also noted. Tables 3 and 4 provide example well data used in the study.

Table 3. Well Data 1 Events, Shuaiba Formation

D, (m)	MW, (gm/cc)	YP, (Ibf/ft^2)	SPM	RPM	Nozzles	Type of losses	Type of Treatment	Result
2993 - 3042	1.15	12	85	70	3*12/32	No Loss	No Treatment	Success
3042 - 3088	1.16	13	85	70	3*12/32	Partial Loss	H.V Mud	Success

Table 4. Well Data 2 Events, Shuaiba Formation

D, (m)	MW, (gm/cc)	YP, (Ibf/ft^2)	SPM	RPM	Nozzles	Type of losses	Type of Treatment	Result
3024	1.17	14	80	65	3*12/32	Complete Loss	H.V Mud	Fail
3024 3038	/	/	80	65	3*12/32	Complete Loss	Blind Drilling	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3017	/	/	80	65	No Bit	Complete Loss	Cement Plug	Fail
3020 - 3038	/	/	80	65	No Bit	Complete Loss	H.V Mud + Cement Plug	Fail
3021 - 3038	/	/	80	65	No Bit	Complete Loss	H.V Mud + Cement Plug	Fail

JMP Statistical Analysis software was used to perform a statistical analysis of the Shauiba mud loss events. Multi-regression analysis was used for modeling because there are multiple drilling parameters, some of which are inter-related. Multi-linear regression models can have multiple independent variables for one dependent variable [7].

It was necessary to first identify which drilling parameters had the greatest impact on the amount of mud losses. Multi-regression analysis identified that ECD had the greatest impact on overall mud losses and ROP had a significant impact on ECD. Hence, three regression models were developed, as discussed here.

All of the drilling parameters were tested in each model to see whether a parameter had a significant effect or a minor impact on the model. This is done using the p-value test. A confidence level of 95% is used to test the significance of each parameter, this means that any parameter with a p-value greater than 5% will be ignored in the model and vice versa.

Using Frontline Solver software, a tornado chart was created as a sensitivity analysis, or impact factor, for the major factors influencing the amount of losses model, ECD model, and ROP model. The purpose of the sensitivity analysis is to examine which parameter has the highest influence in each model and to test the effect of every parameter in all models.

Amount of the Losses Model

Since it was first necessary to identify which drilling parameters had the greatest impact on mud volume loss, a multi-linear regression was performed. Since some parameters are inter-related it was important to show the effect of each parameter on the model using leverage plots. A leverage plot shows the unique effect of adding a term to a model assuming the model contains all the other terms and the influence of each point on the effect of term hypothesis [8]. Points further from the horizontal (blue) line than the slanted (red) line indicate the term has significance while those closer to the horizontal (blue) than the slanted (red) are less significant. A statistically significant leverage plot of any independent parameter has to have a p-value less than 0.05, and a non-zero slope of the red line. If any of the previous conditions are not met, the parameter is not statistically significant and is excluded from the model. Figures 4, 5 and 6 show the leverage plots for MW, ECD, and Yp respectively. The leverage plots of MW, ECD, and Yp have p-values less than 0.05, and the slope of the red line on these plots is non-zero. This make the MW, ECD, and Yp statistically significant parameters.

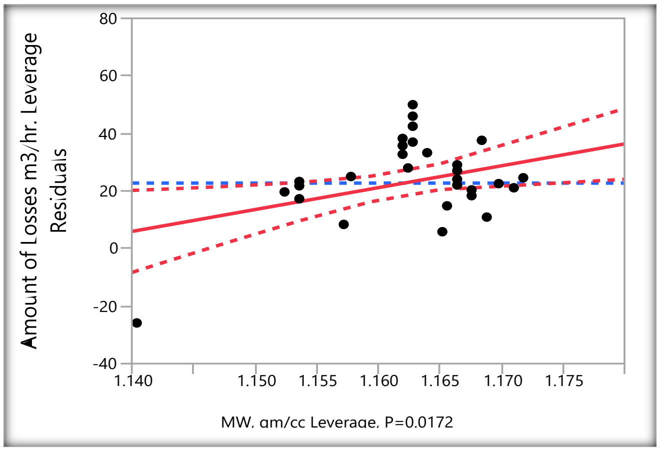

Figure 4. Leverage plot of MW for the Amount of Losses Model

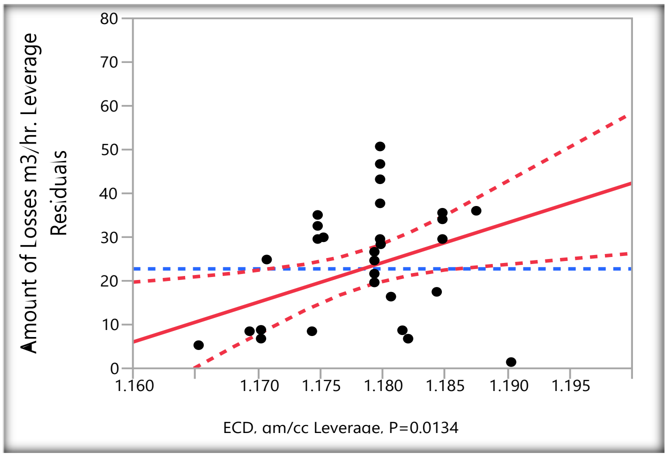

Figure 5. Leverage Plot of ECD for the Amount of Losses Model

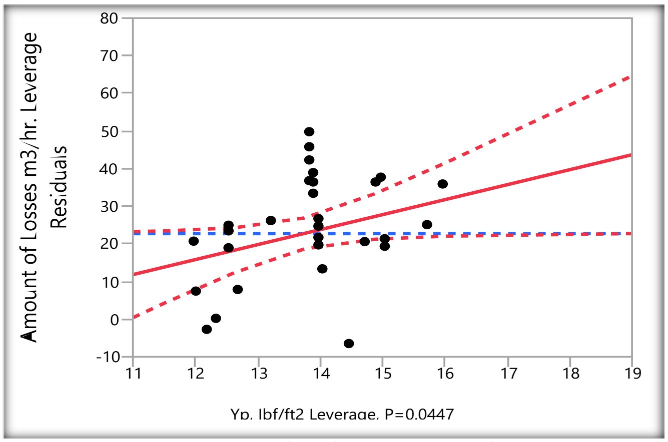

Figure 6. Leverage Plot of Yp for the Amount of Losses Model

Figures 7, 8, and 9 show the leverage plots for the non-significant parameters which are SPM, RPM, and ROP respectively. The leverage plots of SPM, RPM, and ROP have p-values greater than 0.05. This makes SPM, RPM, and ROP non-significant parameters.

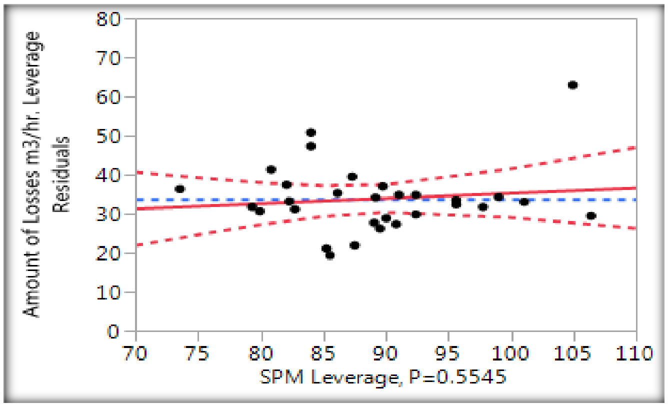

Figure 7. Leverage Plot of SPM for the Amount of Losses Model

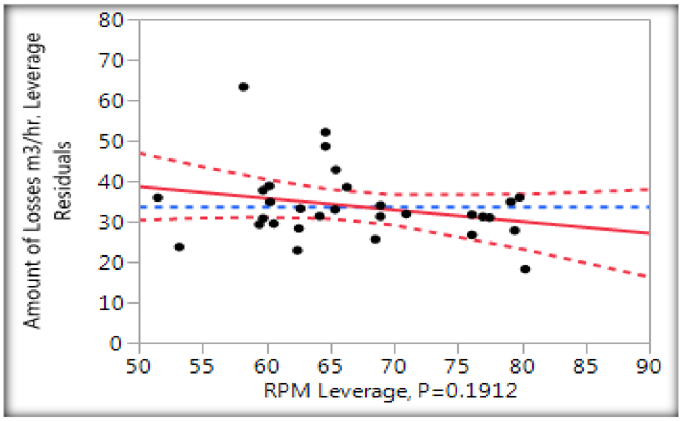

Figure 8. Leverage Plot of RPM for the Amount of Losses Model

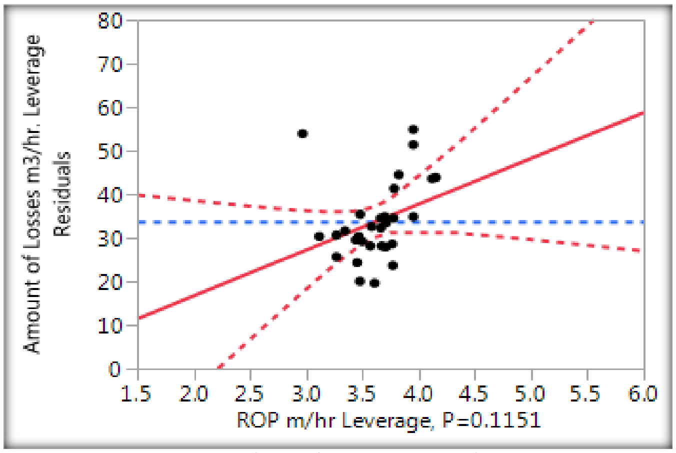

Figure 9. Leverage of ROP for the Amount of Losses Model

ECD, MW and Yp were found to be the significant parameters for the amount of the loss model. This suggests that it is possible to estimate the expected mud volume loss knowing these three drilling parameters. Based on MW, ECD, and Yp, a model to estimate the volume loss was developed to estimate the amount of losses before drilling the Shuaiba formation. The amount of the loss model expressed by equation 1:

$$\mathbf{Losses = -1985 + 760 * MW \left(\frac{gm}{cc}\right) + 908 * ECD \left(\frac{gm}{cc}\right) + 4 * Yp(\frac{lbf}{ft^2})}$$

Figure 10 shows the actual versus the predicted mud losses. The R-squared of this model is 0.827; however, the adjusted R-squared is 0.812. The adjusted R-squared is a modified version of R-squared that accounts for the number of independent variables and should be used for the multi-liner regression [9]. Since there are multiple independent variables, the adjusted R-squared should be used instead of the R-squared.

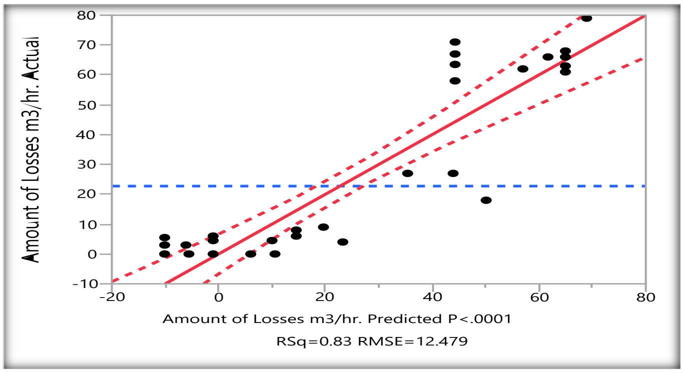

Figure 10. The Actual Versus the Predicted Mud Losses

Figure 11 shows the residual plot for the volume loss model. If the points in the residual plot are randomly distributed (no trend is shown), the linear regression model is valid; otherwise, a non-linear model should be used [9]. The points in the residual plot are randomly distributed. This confirms that a linear regression model is appropriate for the data.

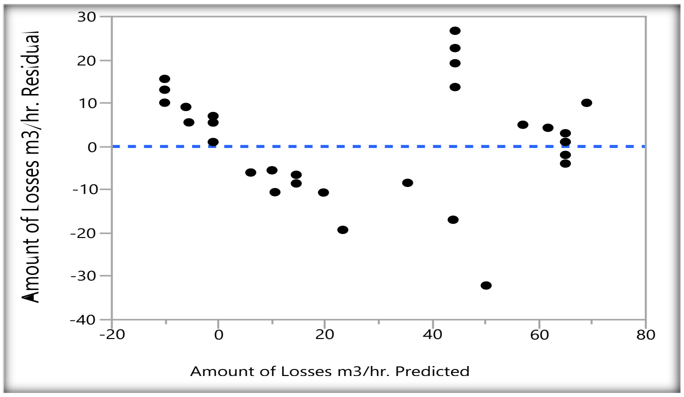

Figure 11. Residual Plot for the Amount of Losses Model

Collinearity (also known as multicollinearity) refers to the condition where two or more independent variables in a multi-linear regression model are highly correlated [10]. Since many drilling parameters are inter-correlated, it is important to also test for collinearity. If collinearity is presented on the model, the variance of at least one independent variable will be inflated. This may flip the sign of at least one of the regression coefficients or it may cause an unstable estimate for one of the linear coefficients [11]. One of the most common methods used to detect collinearity is Variance Inflation Factor (VIF).

The Variance Inflation Factor (VIF) method was used to test for the multicollinearity in the amount of the loss model. Montgomery (2001) suggested that if VIF is greater than 5 or 10, then the regression coefficients are poorly estimated due to multicollinearity. Table 5 shows the summary of the p-values and VIF test. No VIF value exceeded 5. Hence, no multicollinearity is observed in the model.

Table 5. Summary of the P-values and VIF test

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF Test
Intercept	-1985.391	267.7215	-7.42	<.0001	.
ECD, gm/cc	908.04169	348.211	2.61	0.0134	4.8676134
Yp, Ibf/ft^2	3.9816268	1.909781	2.08	0.0447	2.0964192
MW, gm/cc	760.1526	303.5788	2.50	0.0172	3.2701205

Tornado Chart Sensitivity Analysis for the Amount of Losses Model

Figure 12 presents a tornado chart for the three significant parameters (ECD, MW, Yp) and results of the sensitivity analysis. A 10% sensitivity is used in this model. The base parameters are as the following; MW=1.16 (g/cc), ECD=1.2 (g/cc), and Yp=19 ($\frac{\text{Ibf}}{\text{ft}^2}$). Figure 12 shows the impact of each parameter on the amount of the loss model. ECD, in the order of the magnitude of their influence. The amount of the losses is least influenced by the Yp as shown in Figure 12, but Yp is a significant parameter and therefore included in the model.

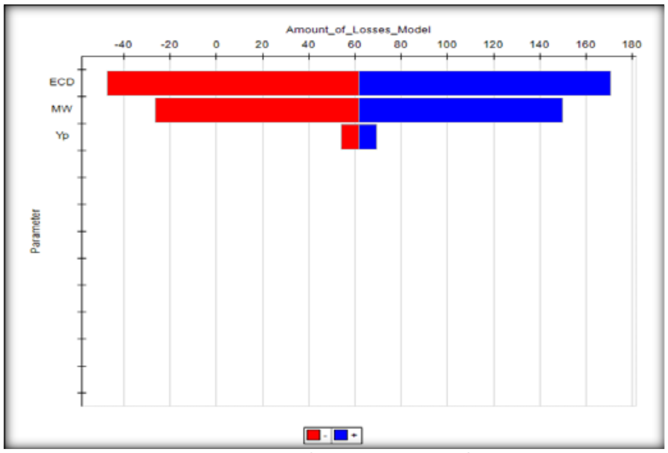

Figure 12. Sensitivity Analysis for the Amount of Mud Losses Model

Equivalent Circulation Density (ECD) Model

After identifying ECD as the most influential parameter in the amount of the mud loss relationship, a multi-linear regression was performed to identify which parameters most affected ECD. After testing the significance of each drilling parameter, only three parameters were found to be significant in determining ECD. These parameters were MW, ROP, and flow rate (Q). Figures 13, 14, and 15 show the leverage plots for MW, ROP, and Q respectively.

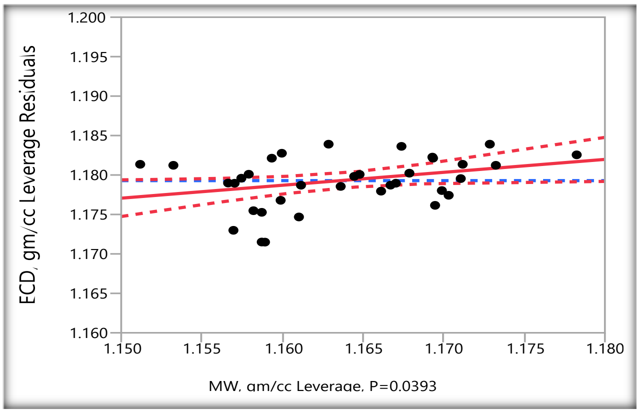

Figure 13. Leverage Plot of MW for ECD Model

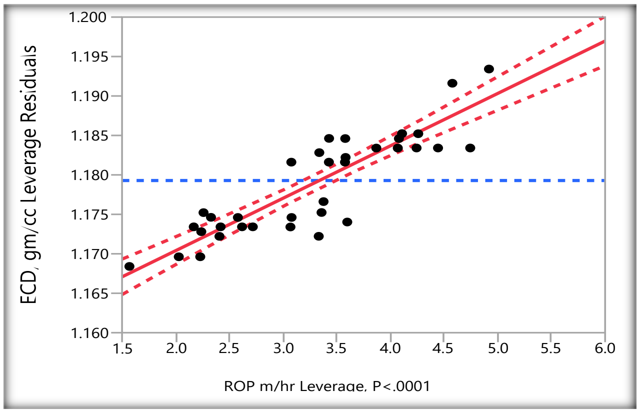

Figure 14. Leverage Plot of ROP for ECD Model

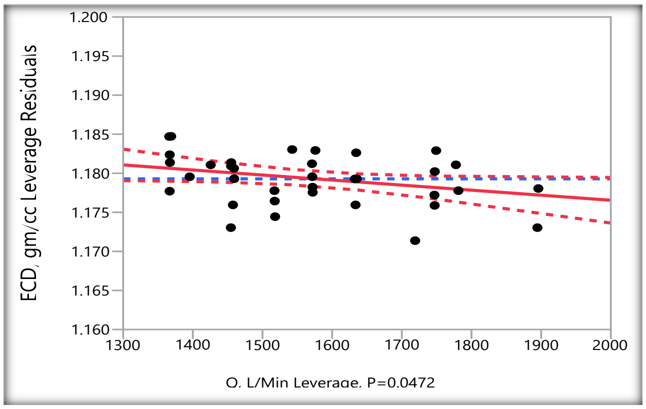

Figure 15. Leverage Plot of Q for ECD Model

Other drilling parameters such as Yp, and RPM were tested to and found to have no significance on ECD. Figures 16 and 17 show the leverage plots for the non-significant parameters which are RPM and Yp respectively.

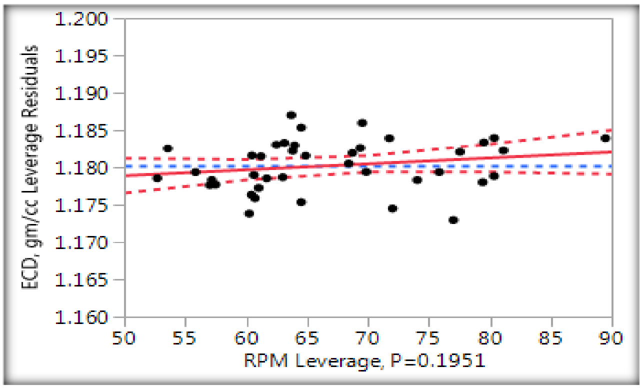

Figure 16. Leverage Plot of RPM for ECD Model

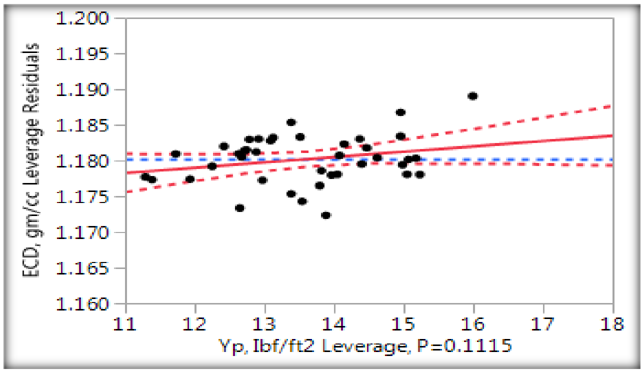

Figure 17. Leverage Plot of Yp for ECD Model

The leverage plots of MW, ROP, and Q have p-values less than 0.05, and the slope of the red line on these plots is non-zero. This means MW, ROP, and Q are statistically significant parameters for determining ECD. However, the leverage plots of Yp and RPM have p-values greater than 0.05. This makes Yp and RPM non-significant parameters.

Based on the multi-regression analysis, it was determined that ECD can be estimated using three parameters, MW, ROP, and Q. The model for calculating ECD is expressed by equation 2 as the follows:

$$\mathbf{ECD = 0.977 + 0.164 * MW\left(\frac{gm}{cc}\right) + 0.00664 * ROP\left(\frac{m}{hr}\right) - 0.00000646 * Q\left(\frac{L}{min}\right)}$$

ECD calculated using equation 2 can be used as an input for Equation 1 (the amount of the mud losses model). ECD is a parameter that can be found during the drilling operation only. Equation 2 provides a good estimation for ECD in the Shuaiba formation.

Figure 18 shows a plot of actual ECD versus the predicted ECD from Equation 2. The R-squared for this model is 0.947, and the Adjusted R-squared is 0.943. Figure 19 shows residual plot for the ECD model. No trend is observed in the data. This suggests that the linear model is valid for this data.

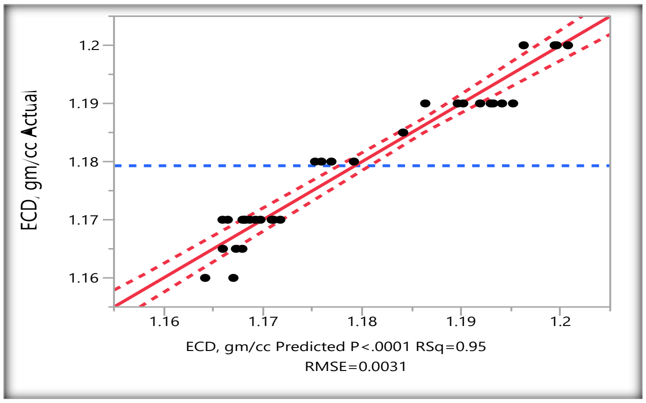

Figure 18. Actual Versus Predicted ECD

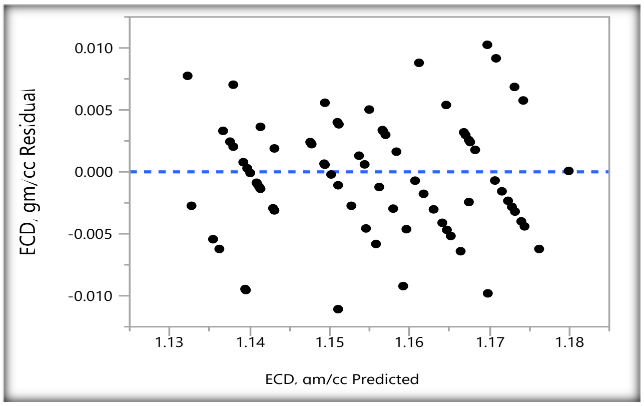

Figure 19. Residual Plot for ECD Model

Table 6 shows the results of the VIF test and p-values. No VIF value exceeded 5. Hence there is no multicollinearity in this model.

Table 6. Summary of VIF and P-values for the ECD Model

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF Test
Intercept	0.9767251	0.0885	11.04	<.0001	.
Q, L/Min	-6.459e-6	3.149e-6	-2.05	0.0472	1.0362324
ROP m/hr	0.0066419	0.000543	12.24	<.0001	3.0797481
MW, gm/cc	0.1637773	0.076717	2.13	0.0393	3.0792094

Tornado Chart Sensitivity Analysis of the Equivalent Circulation Density (ECD) Model

Figure 20 shows a tornado chart of the sensitivity analysis for the ECD model. A 2% sensitivity is used in this model. The base parameters include MW=1.16 (gm/cc), ROP=5.5 (m/hr), and Q=1496 (L/min). Figure 20 shows the influence of each parameter on ECD. As MW and ROP increase, ECD increases; whereas ECD decreases as Q increases.

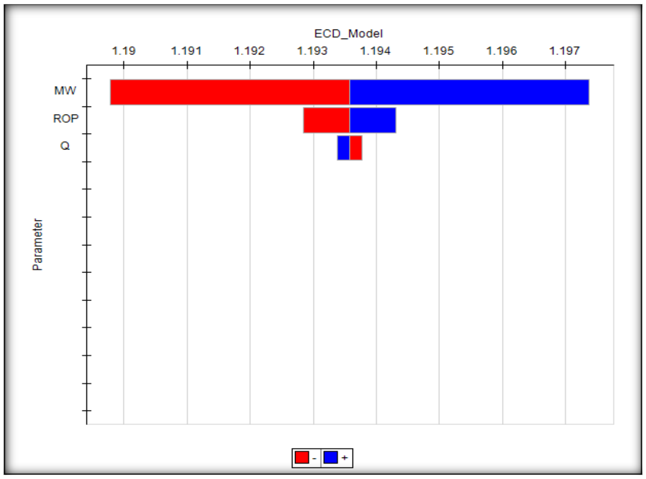

Figure 20. Sensitivity Analysis for the ECD Model

Rate of Penetration (ROP) Model

The final model developed focused on identifying parameters which affected ROP, since ROP was found to be a significant factor of the ECD model (Equation 2). Several drilling parameters were tested to determine their significance. After performing the multi-regression analysis, three parameters, including RPM, SPM and WOB were found to be significant. Figures 21, 22, and 23 show the leverage plots for the significant parameters which are RPM, SPM, and WOB respectively.

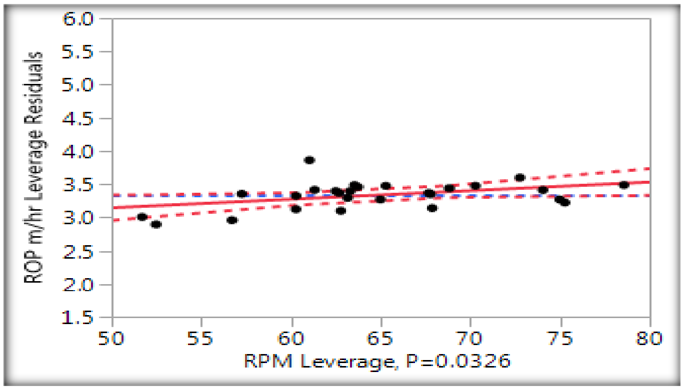

Figure 21. Leverage Plot of RPM for ROP Model

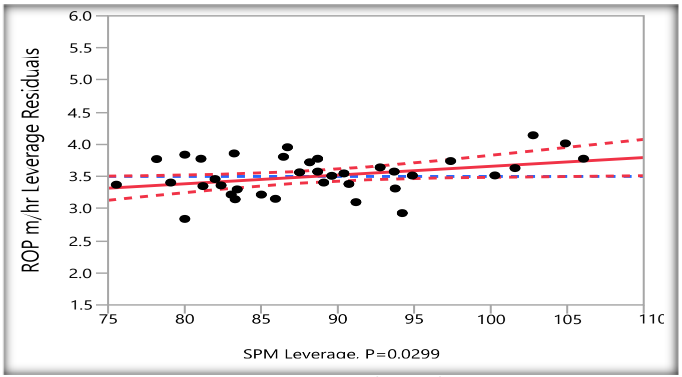

Figure 22. Leverage Plot of SPM for ROP Model

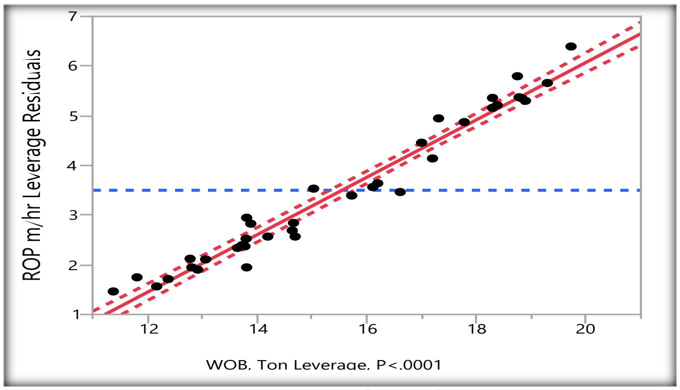

Figure 23. Leverage Plot of WOB for ROP Model

Other drilling parameters, including ECD, MW and Yp were tested for their significance and found to have no impact on the ROP relationship. Figures 24, 25, and 26 show the leverage plots for the non-significant parameters which are ECD, MW, and Yp respectively.

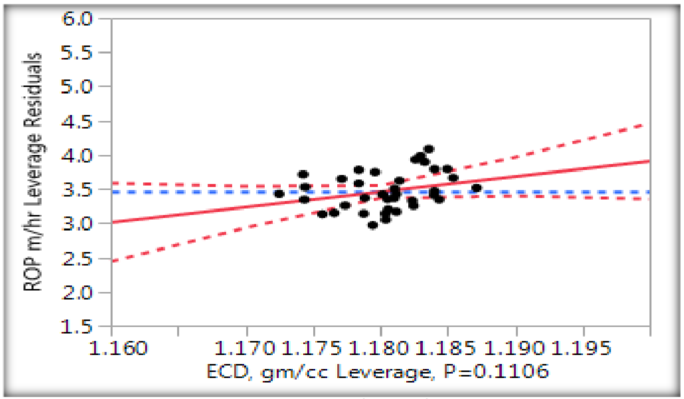

Figure 24. Leverage Plot of ECD for ROP Model

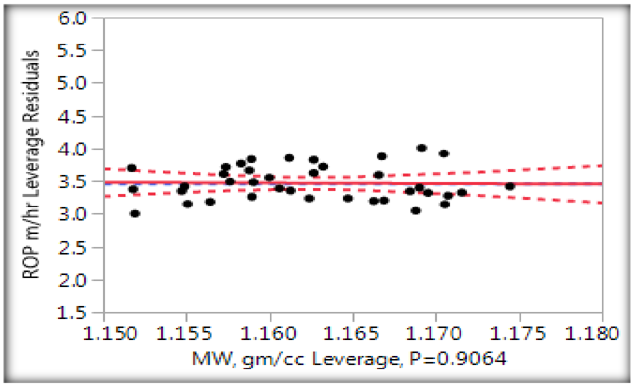

Figure 25. Leverage Plot of MW for ROP Model

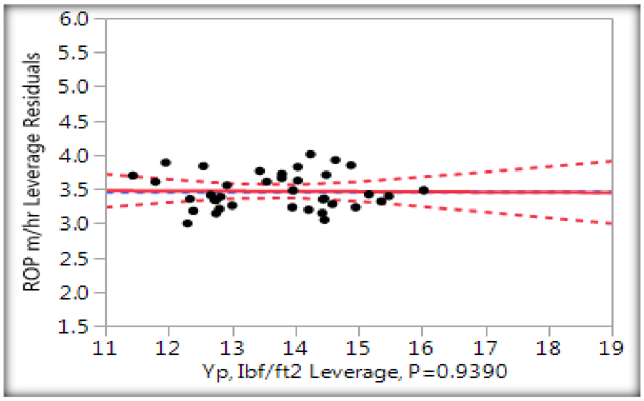

Figure 26. Leverage Plot of Yp for ROP Model

The leverage plots of RPM, SPM, and WOB have p-values less than 0.05, and the slope of the red line on these plots is non-zero. This indicates RPM, SPM, and WOB are statistically significant parameters. However, the leverage plots of ECD, MW, and Yp have p-values greater than 0.05. Hence, ECD, MW, and Yp non-significant parameters in the ROP model.

Based on the multi-regression analysis it was determined that ROP for the Shuaiba formation can be estimated using RPM, SPM, and WOB. The ROP model can be expressed using equation 3 as the follows:

$$\mathbf{ROP = -5.556 + 0.01362 * SPM + 0.01669 * RPM + 0.578 * WOB\ (Ton)}$$

Equation 3 provides a good estimate for the ROP in the Shuaiba formation. In addition, results of equation 3 provide input for Equation 2 (ECD model).

Figure 27 shows a plot of the actual versus the predicted ROP using Equation 3. The R-squared of the model is 0.973, and the adjusted R-squared is 0.971. Figure 28 shows the results of the residual plot for the ROP model. The data are scattered and no trend is observed. Thus, the linear model is valid for the ROP relationship.

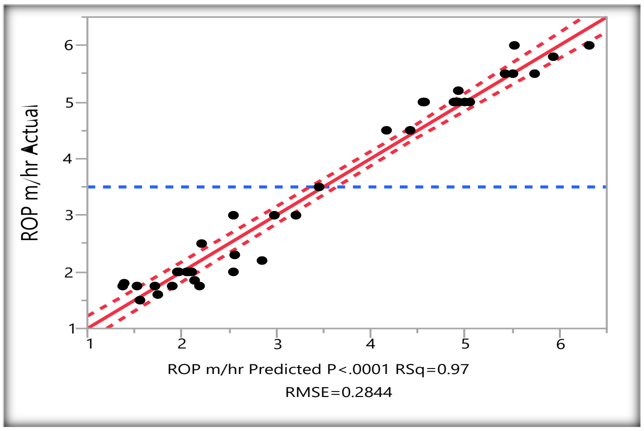

Figure 27. Actual Versus Predicted ROP

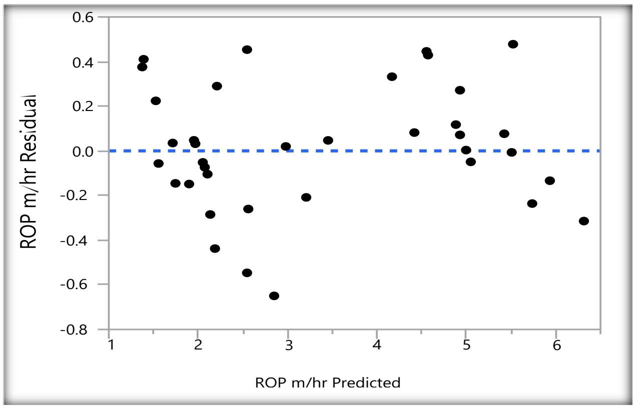

Figure 28. Residual Plot for ROP

Table 7 shows summary results for VIF and p-values. All VIF values are less than 5. Thus, no multicollinearity is observed in the ROP model.

Table 7. Summary of VIF and P-values for the ROP Model

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF Test
Intercept	-5.556436	0.543894	-10.22	<.0001	.
RPM	0.01669	0.005731	2.91	0.0326	1.439719
SPM	0.0136222	0.006031	2.26	0.0299	1.0955306
WOB, Ton	0.578428	0.018594	31.11	<.0001	1.4576531

Tornado Chart Sensitivity Analysis of the Rate of Penetration (ROP) Model

Figure 29 presents a tornado chart showing the sensitivity analysis for the ROP model. A 10% sensitivity is used for the analysis. The base parameters included WOB=19 (Ton), RPM=70, and SPM=85. Figure 29 shows the sensitivity analysis of the ROP model. Results show that ROP is highly influenced by WOB. ROP can be improved by increasing the WOB. The analysis also indicates; RPM affects the ROP more than SPM.

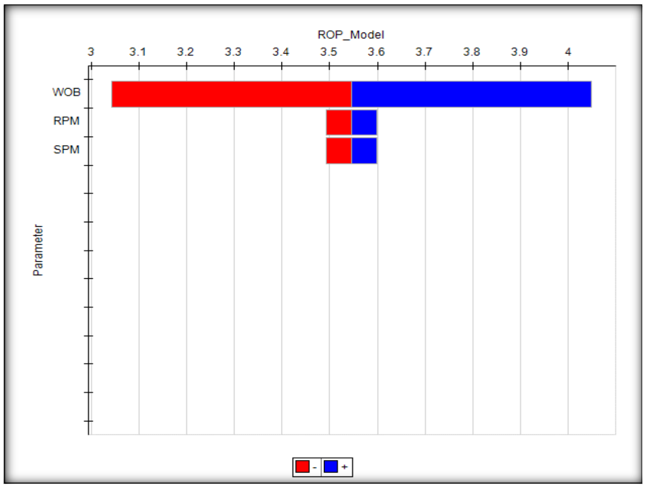

Figure 29. Sensitivity Analysis for the ROP Model

Model Verification and Use

The purpose of this work was to develop a more systematic approach to determining the best values for key drilling parameters while drilling the Shuaiba Formation. The three models developed in the research can be combined to achieve this aim.

Mud volume losses can be predicted for the Shuaiba by first calculating ROP from the inputs to Equation 3. The resulting value for ROP is then combined with values for MW and Q in Equation 2, to calculate ECD. Finally, the calculated value of ECD can be combined with MW and Yp in Equation 1, to calculate a predicted mud loss.

The problem is worked in reverse to determine key drilling parameters. A mud loss plot from Equation 1 can be used to limit overall losses to some value, most likely partial losses. Then, each of the operating parameters can be determined from Equations 1, 2, and 3. This approach provides a method for setting the key drilling parameters to limit losses prior to drilling the Shuaiba formation.

It is important to validate the models prior to field use. Hence, additional the Shuaiba mud loss events data was collected to test each models predicted value (the amount of the mud loss, ECD, ROP) against the actual, new data. Table 8 summarizes the number of mud loss events in new well mud loss events compared to the original events used in the model development.

Table 8 shows the mud loss event counts for original wells used to develop the models and wells used for testing model results. Figures 30, 31, and 32 are plots of predicted values of ROP, ECD and the amount of the mud loss plotted against actual data, respectively. All three figures are for partial losses. There is strong agreement in results for ROP and more variation in ECD. The resulting prediction of mud loss exhibits a strong correlation until 6 m^3/hr. Beyond that point, partial mud losses are more weakly correlated to the model predictions.

Figures 33, 34, and 35 are plots of predicted values of ROP, ECD and the amount of the mud loss against actual data, respectively. All three figures are for severe losses. There is variation agreement in results for ROP and ECD. However, the net result shows a strong correlation between predicted and actual volume losses for severe mud loss events.

Table 8. Summary of the Application of the Real Field Data

Type of the Losses	New Wells	Original Wells	Total New Wells	Total Original Wells	Total Wells
Partial Losses	28	11	62	31	93
Severe Losses	34	20			

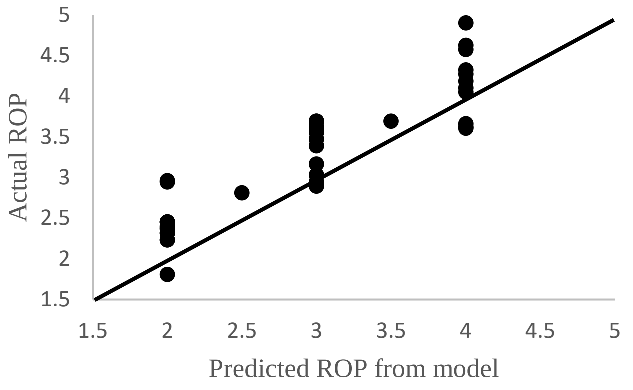

Figure 30. Actual vs. Predicted ROP for Partial Losses

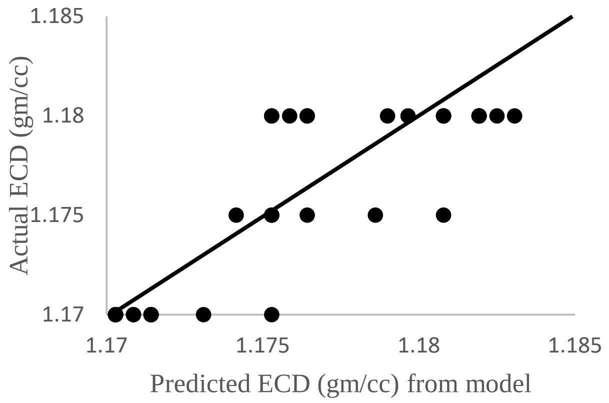

Figure 31. Actual vs. Predicted ECD for Partial Losses

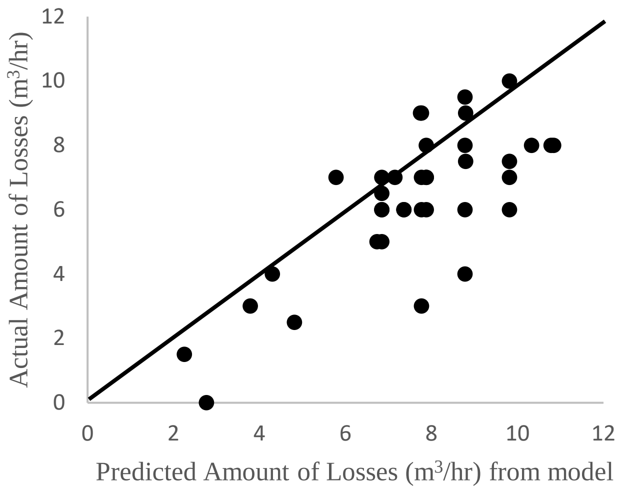

Figure 32. Actual vs. Predicted Amount of Losses for Partial Losses

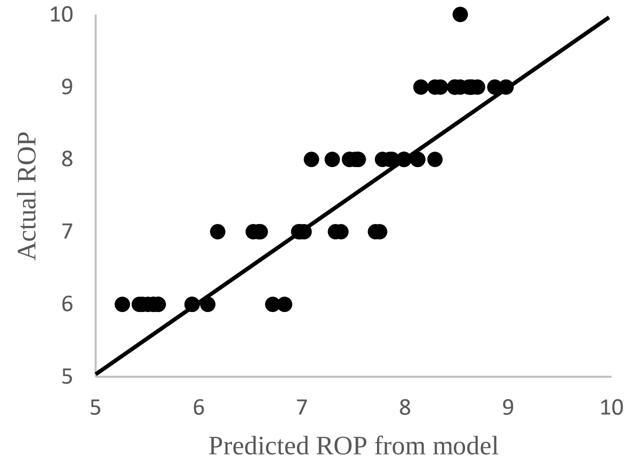

Figure 33. Actual vs. Predicted ROP for Severe Losses

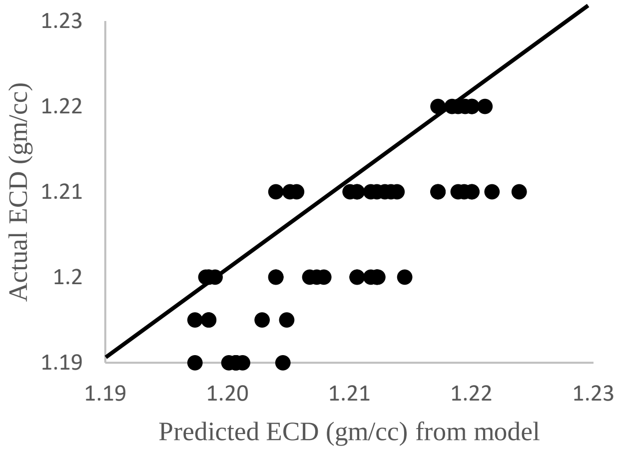

Figure 34. Actual vs. Predicted ECD for Severe Losses

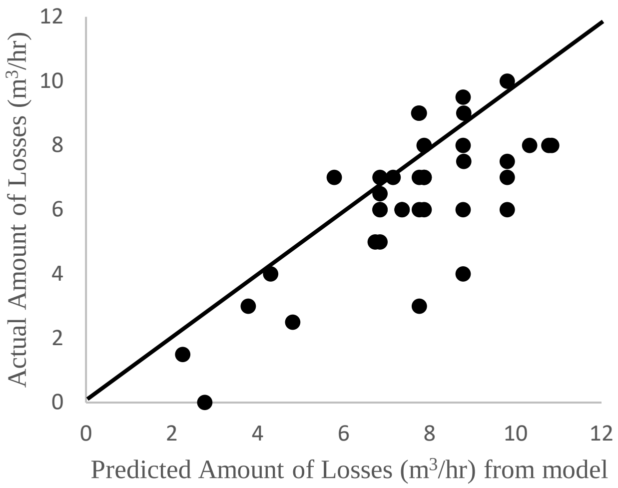

Figure 35. Actual vs. Predicted Amount of Losses for Severe Losses

Conclusions

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 50 wells drilled in the South Rumaila Field. This work identified key parameters affecting mud loss volumes and presents models for setting operational drilling parameters to limit mud losses. Three mathematical models are developed to determine the amount of the mud losses, Equivalent Circulation Density (ECD), and Rate of Penetration (ROP).

The three models developed in this study can be used to estimate expected the amount of the mud losses prior to drilling the Shuiaba formation. Alternatively, given a target loss volume, the models can be used in reverse, to set key drilling parameters to limit losses while drilling.

This model provides greater consistency in the approach to handling mud losses for wells drilled in the South Rumaila Field. The models provide a formalized methodology for responding to losses and provide a means of assisting drilling personnel to work through the mud loss problems in a more systematic way.

- One challenge in drilling wells in the South Rumaila Field is the inconsistency of approaches to the mud losses problem. Hence, a formalized methodology for responding to losses in the South Rumaila Field is developed and provided as means of assisting drilling personnel to work through the mud losses problem in a systematic way.
- The work will provide an integrated analysis regarding the loss problems in terms causes, treatments, and recommendations, and present general practical guidelines to understand this problem in the Shuaiba formation.

Acknowledgments

The authors would like to thank South Oil Company from Iraq and British Petroleum Company for providing us various real field data.

Nomenclature

APL = Annular Pressure Loss
bbl/hr = barrels per hour
BPC = Basra Petroleum Company
BP = British Petroleum Company
DDR = Daily Drilling Report
DOH = Diameter of Open Hole
ECD = Equivalent Circulation Density
F.C = Float Collar
F.S = Float Shoe
gm/cc = gram per cubed centimeter
in = Inch
L/min = Litter per minute
m = meter
m^3/hr = cubed meter per hour
MW = Mud Weight
NPT = Non-productive Time
Q = Flow Rate
ROP = Rate of Penetration
RPM = Revolutions per Minute
SPM = Stroke per Minute
VIF = Variance Inflation Factor
WOB = Weight of Bit
WON = Without Nozzles
Yp = Yield Point Viscosity

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