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Limiting key drilling parameters to control mud losses in Basra's oil fields, Iraq

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LIMITING KEY DRILLING PARAMETERS TO CONTROL MUD LOSSES IN BASRA'S OIL FIELDS, IRAQ

by

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This dissertation consists of the following four articles, formatted in the style utilized by Missouri University of Science and Technology. Paper I, comprising pages 7 through 26, is published as a conference paper to the Society of Petroleum Engineering, under the title ‘‘New Classification of Lost Circulation Treatments and Materials with an Integrated Analysis and Their Applications’’. Paper II, comprising pages 27 through 64, is published as a journal paper to Egyptian Journal of Petroleum, under the title ‘‘Real-Time Lost Circulation Estimation and Mitigation’’ Paper III, comprising pages 65 through 90, is published as a journal paper to Journal of Petroleum & Environmental Biotechnology, under the title ‘‘Big Data Analysis Identifies Effective Lost Circulation Solutions in the Hartha Formation”. Paper IIII, comprising pages 91 through 123, is published as a conference paper to the American Association of Drilling Engineers, under the title ‘‘A New Approach to Reduce Lost Circulation Non-Productive Time”.

ABSTRACT

Wells in Basra’s oil fields are highly susceptible to lost circulation problems when drilling through the Dammam, Hartha, and Shuaiba formations. Drilling engineers are challenged to select the optimum value for key drilling parameters such as ECD, Yp, MW, WOB, ROP, and RPM to mitigate mud losses in these formations. Many of these drilling parameters are inter-related and the overall impact of changing key parameters require extensive drilling experience and study. A multi-regression analysis was performed on mud loss event data for more than 300 wells drilled in Basra’s oil fields. From this analysis, a model was developed to predict the total mud losses. Mud loss was found to be significantly affected by MW, ECD, and ROP. Models for ECD and ROP were also developed from the multi-regression analysis.

In the same vein, proactive approaches are made prior entering the Dammam, Hartha, and Shuiaba formations to prevent or mitigate the occurrence of the lost circulation. Key drilling parameters are estimated to use during drilling through these formations. In case preventive measures didn’t work, corrective actions are determined for each type of the mud losses to provide effective remedies, minimize NPT, and reduce cost.

This dissertation will contribute toward a better understanding of how the different factors could affect the lost circulation which is believed to have a significant impact on the mitigation mud losses. Therefore, optimized preventive and corrective solutions will be designed for combating lost circulation.

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SECTION

1. INTRODUCTION

The technology in the oil and gas industry has evolved over the years. This has led to many production from areas that were never thought to be discoverable. As a result, the drilling environment has become more difficult. One of the most common problems related to drilling is the problem of lost circulation. This problem is very challenging and not easy to combat, especially with hostile drilling environments. Lost circulation can happen in permeable formation, naturally fractured or induced fractured formations, and caves and vugs. Lost circulation while drilling is defined as the partial or total fluid lost in the formation due to the aforementioned reasons (Moore, 1986; Osisanya, 2002). The oil and gas industry spends millions of dollars every year to provide proactive and corrective solutions to the problem of lost circulation. Nonetheless, there is not any systematic solution to the problem of lost circulation.

Lost circulation can be classified into four major types, based on the amount of fluid lost to the formation as; seepage loss, partial loss, severe loss, and complete loss. Seepage loss (1 m^3/hr or less) is similar to filtration. It is desired to have filtration to provide a thin mud cake to have a stable well. The key is to “control” filtration not totally stopping it. Partial loss (1-10 m^3/hr) is more difficult than seepage loss. Severe loss (greater than 15 m^3/hr) is not easy to control since the fluid lost is large, and if not handled properly, it may lead to a complete loss where no return of fluid is observed at the surface (Basra Oil Company, 2012). Each type of lost circulation can be mitigated, controlled, or stopped in various ways.

There are many proactive and corrective methods to mitigate or stop lost circulation. Nevertheless, there is not any systematic approach in the literature that provides a clear path on how to handle the lost circulation problem in the oilfield. Therefore, there is a need for a standardized approach that can clearly guide the drilling personnel on how to properly handle the lost circulation problem.

This work provides a systematic proactive and corrective approaches to the problem of lost circulation using machine learning and data mining techniques. The ultimate goal is to minimize the non-predictive time related to the problem of lost circulation in order to optimize the drilling operation and save time and money.

1.1. OBJECTIVES OF THE STUDY

The main aims of this work can be summarized as the following

1. To provide a new classification for mud loss corrective and proactive methods used by the oil & gas industry.
2. To gather data of the key drilling parameters affecting lost circulation from many wells drilled in Iraq.
3. To collect lost circulation treatment data based on the type of loss.
4. To utilize machine learning and other statistical methods to create models that can predict mud loss for three formations in Basra city, Iraq (Dammam, Hartha, and Shuaiba) prior to drilling. Then, provides recommendations of key drilling parameters that can mitigate the lost circulation problem.
5. Since mud loss is affected by equivalent circulation density (ECD), and ECD can only be calculated while drilling using hydraulics, an empirical equation was

created to estimate ECD prior to drilling the aforementioned formations. In addition, ECD is affected by the rate of penetration (ROP), which is also acquired while drilling. Thus, an empirical equation was created to estimate ROP prior to drilling.

6. To perform a sensitivity analysis to understand the effect of each key drilling parameter on the lost circulation problem.
7. To use data mining techniques to classify the mud loss treatments depending on the type of loss. Then, to come up with the best lost circulation treatment strategy for each type of loss.

1.2. RESEARCH METHODOLOGY

Originally, a novel tabulation of mud losses actions is evolved, which are uniquely different from the previous studies, the novel sorting is according to the complexity of the remedies and the loss type. Moreover, the remedies are re-categorized as preventive and remedial approaches in order to provide an efficient action and to minimize the non-productive time, which is associated to this kind of problem.

Then, mud loss events for more than 300 wells drilled in the Rumaila field were identified through reading and summarizing daily drilling reports (DDR), final well reports, and technical report. Critical drilling parameters such as mud weight (MW), equivalent circulation density (ECD), yield point (Yp), rate of penetration (ROP), strokes per minute (SPM), flow rate (Q), revolution per minute (RPM), plastic viscosity (PV), 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.

The multiple linear regression analysis was used for modeling because there are multiple drilling parameters, some of which are inter-related. Multiple linear regression models can have multiple independent variables for one dependent variable. It was necessary to first identify which drilling parameters had the greatest impact on the amount of mud losses. Multiple linear 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.

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. After finishing building the models, new data were obtained (data not included in building the models) to test the efficiency of the models with the new data.

Also, 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.

Finally, recommended key drilling parameters have been determined in this dissertation to prevent or mitigate lost circulation in the Dammam, Hartha, and Shuaiba formation. This is done based on reviewing data of key drilling parameters. In addition, mud losses treatments events are examined, and statistical analysis is conducted for these remedies. The probability of each treatment is calculated by adding the number of times they were used successfully divided by the total number of attempts. An economic evaluation is performed for the same data based on the cost of each material and the NPT, the rig cost is estimated to be 36000 ($/day). Thus, the lost circulation strategy has been developed by depending on statistical work and economic analysis to efficiently remedy in terms of stopping mud losses, minimizing non-productive time, and reducing cost. Practical field information from a range of sources was reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in these formations.

1.3. DATA RESOURCES

Collecting data is very time-consuming. The available data were not in a consistent format and each parameter used in this work was acquired manually by digging through pdf files and obtaining these parameters. The total number of wells used in this study is 300 wells drilled in Basra city in Iraq. Below is a summary of the data used in this study:

1. Literature is the first data source used in this study. Many data were gathered from published articles in the literature in order to comprehend the current usage of lost circulation treatments by the oil and gas industry.
2. Well logs data source used to understand the formations that studied in this work (Dammam, Hartha, and Shuaiba).
3. Daily drilling reports (DDR) are used to export the mud loss events in addition to the treatments used for each type of mud loss.

4. Mud logging reports are invested to understand the change in mud weight after drilling some formations. The mud logger accesses the shape and the size of the cutting to have more insights into the drilling operations.
5. Cementing reports are utilized for post-application performance evaluation of the treatments.
6. Final wells reports have economic information and all details related to drilling the wells.

PAPER

I. A NEW CLASSIFICATION OF LOST CIRCULATION TREATMENTS AND MATERIALS WITH AN INTEGRATED ANALYSIS

ABSTRACT

Mud losses are considered one of the major contributors to drilling non-productive time (NPT). Among the top ten drilling challenges facing the oil and gas industry today is the problem of lost circulation. Enormous effort has been undertaken to understand the mechanics of lost circulation control. Lost circulation control during well construction is more than just selecting the right lost circulation material (LCM) but requires a complete engineered approach. Some of the approaches involve borehole stability analysis, equivalent circulating density (ECD) modelling, leak-off flow-path geometry considerations, drilling fluid and LCM selection to help minimize effects on ECD, on-site monitoring using annular pressure while drilling (APWD), and timely application of LCM and treatments.

Lost circulation materials (LCM's) have been widely used to stop or mitigate losses. Due to a large number of current available LCM's and their different applications, classification and testing of LCM's are very important. Conventional LCM's are currently classified into different categories based on their appearance as fibrous, flaky, and granular or a blend of all three. The most recent LCM classification was published around 50 years ago, and this paper intends to fill this gap with an updated classification and their applications including conventional and new technologies. Lost circulation materials and

treatments are re-classified into various categories based on their appearance, applications, chemical and physical properties.

This paper classifies the lost circulation materials and treatments as corrective and preventive approaches. The corrective treatments can be applied after the occurrence of the lost circulation; however, the preventive techniques can be applied before entering losses zones as a proactive action. The most recent developments in lost circulation materials and treatments are discussed, in addition to the presentation of a comprehensive summary of today's available LCM's, treatments and alternative approaches with their applications.

1. INTRODUCTION

Lost circulation is a phenomenon in which the drilling fluid flows into one or more geological formations instead of returning to the annulus and surface. Because of this, the oil industry suffers a loss of over one billion dollars annually in rig time, materials, and other financial resources (Aadnoy et. al, 2007). Lost circulation is a common drilling problem especially in highly permeable formations, depleted reservoirs, and fractured or cavernous formations. The range of lost circulation problems begin in the shallow, unconsolidated formations and extend into the well-consolidated formations that are fractured by the hydrostatic head imposed by the drilling mud (Moore, 1986).

Lost circulation is a common drilling problem especially in highly permeable formations, depleted reservoirs, and fractured or cavernous formations as shown in Figure 1 (Nayberg and Petty, 1986). The range of lost circulation problems begin in shallow, unconsolidated formations and extend into the well-consolidated formations that are fractured by the hydrostatic head imposed by the drilling mud (Moore, 1986). By industry estimates, more than 2 billion USD is spent to combat and mitigate this problem each year (Arshad et al., 2015). Two conditions are both necessary for lost circulation to occur down hole: 1) the pressure in the wellbore must exceed the pore pressure and 2) there must be a flow pathway for the losses to occur (Osisanya, 2002). Subsurface pathways that cause, or lead to, lost circulation can be broadly classified as follows:

1. Induced or created fractures (fast tripping or underground blow-outs).
2. Cavernous formations (crevices and channels).
3. Unconsolidated or highly permeable formations.
4. Natural fractures present in the rock formations (including non-sealing faults).

The rate of losses is indicative of the lost pathways and can also give the treatment method to be used to combat the losses. The severity of lost circulation can be grouped into the following categories (South Oil Company, 2012):

1. Seepage losses: up to 1 m^3/hr lost while circulating.
2. Partial losses: 1 – 10 m^3/hr lost while circulating.
3. Severe losses: more than 15 m^3/hr lost while circulating.
4. Total losses: no fluid comes out of the annulus.

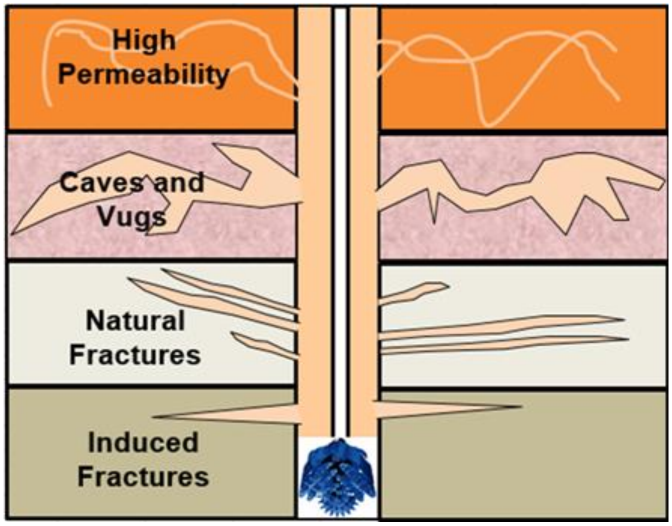

Figure 1. Candidate Formations for Losses Events (Alkinani et al., 2020)

One of the early efforts to cure losses or prevent them from happening by adding granular materials to the drilling fluid was introduced by M T. Chapman in 1890. Since then, lost circulation materials have been widely used to stop or mitigate drilling fluid losses into the formation. LCM’s are added continuously to the drilling fluid system or spotted as a concentrated LCM’s pill to seal naturally existing fractures or induced fractures that are produced while drilling.

2. METHODOLOGY

The aim of this work is to update the classification of lost circulation treatment and materials. The current lost circulation materials are classified into four categories; granular, flaky, fibrous, and mixture of LCM's. The current classification is based on the physical properties only and it is 50 years old, thus a new classification is required to follow the developments in the industry. This paper was developed mostly based on the literature with real field data from Basra's oil fields. More than 200 technical journals, papers, textbooks, cases histories, real fields data, and manuals that address the problem of lost circulation are carefully reviewed and summarized. Lost circulation materials and treatments are extracted from the literature. The results from the lab are compared to what was applied on many oil fields including 800 wells drilled in Basra's oil fields.

A new classification for lost circulation treatments and materials is developed. Unlike the current classification, the new classification is based on the appearance, applications, chemical, and physical properties. In addition, the lost circulation materials and treatments are re-classified into two major categories, proactive and corrective methods. The proactive are applied prior to entering the losses zone. However, the corrective is applied after the occurrence of lost circulation. Finally, all materials and treatments for the proactive and corrective methods are summarized in tables with their executive procedures.

3. LOST CIRCULATION TREATMENT: CORRECTIVE VS. PREVENTATIVE

The way that lost circulation treatments are applied could be classified based on the time when these treatments were implemented. It can be either before (preventive) or after (corrective) the occurrence of the lost circulation event:

3.1. CORRECTIVE METHODS

This section demonstrates the various lost circulation treatment materials and their application. The treatments are categorized into general groups to assist in describing the way they work and to differentiate their applications. A wide range of bridging or plugging materials is available for reducing lost circulation or restoring circulation while drilling or cementing a well. Each lost circulation material is selected by depending on timing, type of losses, cost, phase drilling, mud type, and type of formation. Lost circulation materials and treatments are used to achieve two goals:

1. To bridge across the face of fractures and vugs that already exist.
2. To prevent the growth of any fractures that may be induced while drilling.

Table 1 will be demonstrated the conventional LCM's, which are currently classified into different categories based on their appearance as fibrous, flaky, and granular or a blend of all three. However, Table 2 to 5 will be illustrated the lost circulation materials and treatments, which are re-classified into various categories based on their appearance, applications, chemical and physical properties.

Table 1. Current LCM's and Treatments Classification with their Applications (Howard and Scott, 1951; Nayberg and Petty in 1986; Ali et al., 1994; Pilehvari and Nyshadham, 2002; Jiao and Sharma, 1995)

Name	Type of Losses	Formation's Problem
Granular	Seepage, Partial, and Severe	Permeable, Cavernous/Vugular, and Natural Fracture Formations
Flaky	Seepage, Partial, and Severe	Permeable, Cavernous/Vugular, and Natural Fracture Formations
Fibrous	Seepage, Partial, and Severe	Permeable, Cavernous/Vugular, and Natural Fracture Formations
Mixture of LCM's	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures

Table 2. Updated LCM's and Treatments Classification with their Applications for Seepage Losses

Name	Type of Losses	Type of Mud	Formation's Problem	Drilling Phase
Bentonite	Seepage	FWBM, OBM, FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)
Polymers	Seepage	KCL Mud, Polymer Mud, Lime Mud	Any type of formation	(Pf >Pp)
CMC-LV	Seepage	FWBM, OBM, FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)
CMC-HV	Seepage	FWBM, FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)
Starch	Seepage	SWBM, KCL Mud, Lime Mud, Lime Mud	Any type of formation	(Pf >Pp)
PACR-LV	Seepage	FWBM, Polymer Mud, KCL Mud, Lime Mud	Any type of formation	(Pf >Pp)
PACR-HV	Seepage	FWBM, Polymer Mud, KCL Mud, Lime Mud	Any type of formation	(Pf >Pp)
SPA	Seepage	FWBM, OBM, FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)
Lignins and Tannins	Seepage	FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)
Resinex	Seepage	OBM, KCL Mud, FCL Mud, FCL-CL Mud	Any type of formation	(Pf >Pp)

Table 3. Updated LCM's and Treatments Classification with their Applications for Partial Losses

Name	Type of Losses	Formation's Problem	Drilling Phase
High Viscosity Patch	Partial	Gravels, Small Natural Fractures, and Permeable Formations	(Pf ≥Pp)
Granular	Partial	Gravels, Small Natural Fractures, and Permeable Formations	(Pf ≥Pp)
Flaky	Partial	Gravels, Small Natural Fractures, and Permeable Formations	(Pf ≥Pp)
Fibrous	Partial	Gravels, Small Natural Fractures, and Permeable Formations	(Pf ≥Pp)
Plugging Materials	Partial	Gravels, Small Natural Fractures, and Permeable Formations	(Pf ≥Pp)
Mixture of LCM's	(Severe≤ 20 m^3/hr.)	Medium Natural Fractures, Small or Medium Cavernous/Vugular Formations	(Pf >Pp)

Table 4. Updated LCM's and Treatments Classification with their Applications for Severe Losses

Name	Type of Losses	Formation's Problem	Drilling Phase
High Fluid Loss, High Strength Pills	Severe > 20 m3/hr.	Fractured or Highly Permeable Formations	(Pf>>Pp)
Swellable/Hydratable LCM's Combinations	Severe > 20 m3/hr.	Large Cavernous/Vugular and Large Nature Formations	(Pf>>Pp)
Super Stop Material	Severe > 20 m^3/hr.	Highly Permeable Formations	(Pf>>Pp)
H.V Drilling Mud (Low Density) + Blend of LCMs	Severe > 20 m^3/hr.	Induced Fracture	(Pf>FG)
Cement Plug	Severe > 20 m^3/hr.	Induced Fracture	(Pf>FG)
High Filtration Spot Pills, High Filtration Mixtures (200-400 cc API)	Severe > 20 m^3/hr.	Highly Permeable Formations	(Pf >>Pp)
High Filtration Spot Pills, very high filtration mixtures (> 600cc API)	Severe > 20 m^3/hr.	Highly Permeable Formations and Large Cavernous/Vugular	(Pf>>Pp)
Precipitated Chemical Slurries, Silicate and Latex	Severe > 20 m3/hr.	Induced Fracture	(Pf>FG)

Table 5. Updated LCM's and Treatments Classification with their Applications for Complete Losses

Name	Type of Losses	Formation's Problem	Drilling Phase
Cement Slurries Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Cross-Linked Cements (CC) Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Gilsonite Cement Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Fiber in Cement Slurry Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Gunk Slurries Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Attapulgite Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Dilatant Slurries Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
InstandSeal Plugs	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)
Barite Plug	Complete	Highly Natured Fractures, Interconnected Large Vugs, and to Widely Open Induced Fractures	(Pf>FG)

3.2. PREVENTIVE METHODS

Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al., 2005). All those remedies/techniques that are applied prior to entering lost circulation zones to prevent the occurrence of losses can be defined as proactive methods. The overall objective of this method is to strengthen the wellbore (Withfill, 2008). The concept of wellbore strengthening can be defined as "a set of techniques used to efficiently plug and seal induced fractures while drilling to deliberately enhance the fracture gradient and widen the operational window" (Salehi and Nygaard, 2012). This approach depends on propping or sealing the fractures using LCM's (Salehi and Nygaard, 2012). The main advantage of using wellbore strengthening is to increase the fracture gradient of the formation and the hoop stress. This provides an opportunity to use higher mud weight windows for drilling, especially, weaker and depleted formations. In different words, by using wellbore strengthening approach, the range of the mud weight window will increase. Wellbore strengthening methods generally use in order to get the following targets (van Oort et al., 2009):

1. Enhance the near-wellbore stress by increasing hoop stress, thus raising the threshold for fracture re-opening and growth.
2. To increase the design range of the mud weight window.
3. Increase the formation's resistance to fracture propagation.

In this section. Table 6 will mention proactive approaches that have already been used to increase wellbore strengthening.

Table 6. Modern Technologies for Preventive Approaches (Wang et al. (2005), Riley et al. (2012), Hoelscher et al. (2012), Sharma et al. (2012), Nwaoji et al. (2013), Contreras (2014), Wang (2011), Sanders et al. (2010), Kumar et al. (2010))

Name	Description
Nanoparticles	• Solid particles (1-100 nm) • Seals micro fractures • Permeability reduction in shale • Wellbore Strengthening application
Plug Forming Assurance	• Developed to address fracture size and shape uncertainties • Uses 2 components; deformable foam wedges and fine particles
Customized Combinations	• Will have a wide range of PSD and different physical properties • Combining 2 or more LCM's will improve the overall performance • Often optimized as a function of PSD
Resilient Graphitic Carbon (RGC)	High performance material as proactive treatment and wellbore strengthening: Resilient graphitic carbon (RGC) is one of the most successful materials in preventing lost circulation mud.
Chemical Grout	This treatment is chemical consolidation mechanism that has been proved as effective way in underground openings for many years. This method is usually used inhibit water influx into well and to increase rock strength as wellbore strengthening approach.
Deformable, Viscous, And Cohesive Systems (DVC)	This method is usually used for strengthening the zone. DVC sealant may deform under pressure or stress. Deformation of this seal has ability to maintain the seal and isolate the fracture tip from the wellbore pressure.
Resin treatment (Formation consolidation and chemical casing method)	In this method, water dispersible resins are used to increase rock strength and support weak zones. There are various kinds of resins that have already used like epoxies, phenolic, and furans to control for wellbore stability.
CaCO3	It is readily available and can easily be added to LCM spot pills in high concentrations. It can be added in circulation as prevention. It is one of the most successful materials in preventing lost circulation mud.

4. SUMMARY OF THE WORK

Lost circulation presents many challenges while drilling. To address these problems, several methods/techniques have evolved over the years. The objectives of this study are: 1) to review lost circulation control methods that have been applied in the drilling industry till date 2) to provide an updated classification of these materials and treatments with field applications and 3) to develop practical guidelines that will serve as a reference material for lost circulation control at the well-site for drilling personnel.

To achieve these study objectives, a selected number of technical journals, papers, textbooks, cases histories, real fields data, and manuals that address the problem of lost circulation were carefully reviewed and summarized. The results of this study are practical guidelines that are not biased towards a particular service industry product but are general to the mitigation of the problem of lost circulation while drilling. A flowchart in Figure 2 has also been developed that will serve as a quick reference guide for drilling personnel at the well-site.

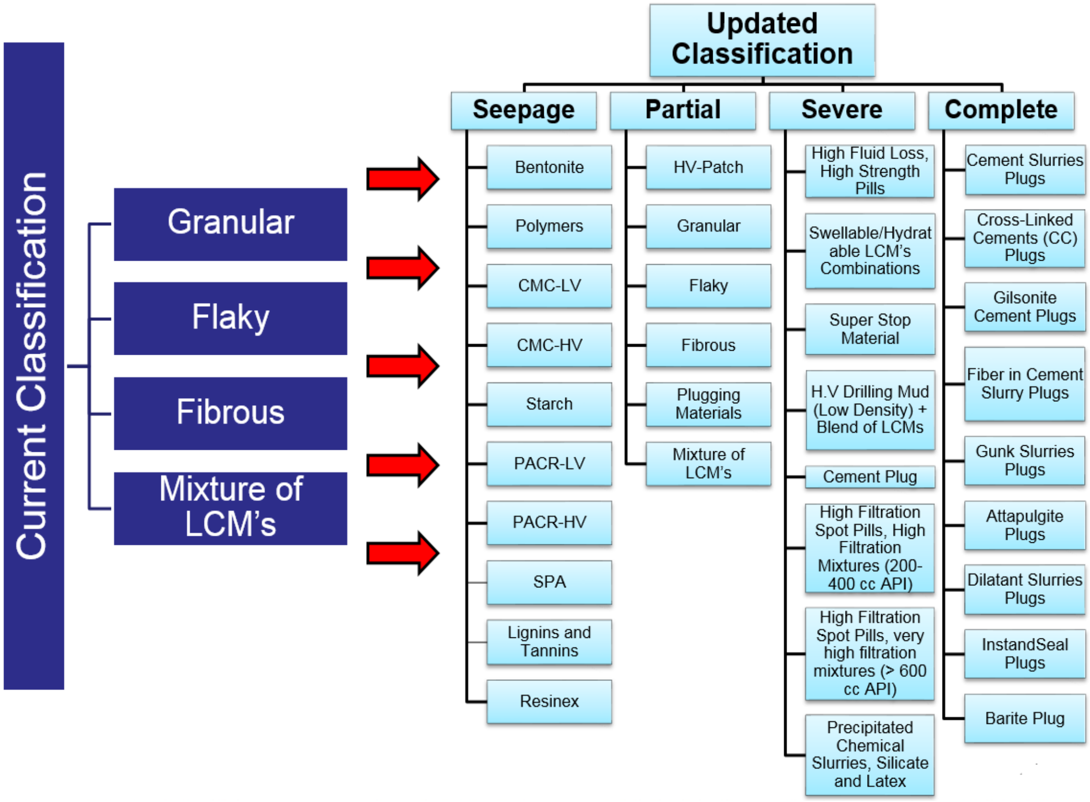

Figure 2. Current and an Updated Classification of the Lost Circulation Materials and Treatments

5. CONCLUSION

This paper constructs a new LCM's classification that can serve as a reference and guideline for operators, service companies, and drilling industry in general to properly classify the materials used to control, mitigate or avoid lost circulations. Lost circulation materials and treatments are re-classified into various categories based on their appearance, applications, chemical and physical properties. The authors believe in the significance of classification the lost circulation materials and treatments based on timing, type of losses, cost, phase drilling, mud type, and type of formation. Lost circulation materials and treatments are categorized with the target of creating a unique technical approach to help the drilling personnel mitigating or stopping lost circulation.

Based on this study, the following conclusions were made:

1. Granular, flaky, and fibrous are used for partial losses only. Mixture of them can be used for severe losses ≤ 20 m^3/hr.
2. Lost circulation materials and treatments are re-classified into various categories based on their appearance, applications, chemical and physical properties.
3. Modern technologies for preventive treatments are summarized and tabulated.
4. There is a large gap in evaluating LCM's for preventive treatments applications.
5. Industry collaboration to address and discuss this topic will benefit the entire drilling industry.

NOMENCLATURE

Symbol	**Description**
APWD	Annular Pressure While Drilling
$CaCO_3$	Calcium Carbonate
CC	Cross Linked Cement
CMC-LV	Carboxymethly Cellulose (Low Viscosity)
CMC-HV	Carboxymethly Cellulose (High Viscosity)
DOB	Diesel Oil Bentonite
DOBC	Diesel Oil Bentonite Cement
DVC	Deformable Viscous Cohesive
ECD	Equivalent Circulation Density
FCL	Ferro Chrome Lignosulfonate
FCL-CL	Ferro Chrome Lignosulfonate- Chrome Lignite
FP	Fracture Pressure
FG	Fracture Gradient
FWB	Fresh Water Bentonite
H.V	High Viscosity
Ib/bbl	pounds per barrel
Ib/ft^3	pounds per cubed feet
ID	Internal Diameter
in	Inch
LCMs	Lost Circulation Materials

m	meter
m^3/hr	cubed meter per hour
MCC	Magnesia Cross-Linked Cement
MW	Mud Weight
NPT	Non-productive Time
OBM	Oil Base Mud
PAC-LV	Low Viscosity Polyanionic Cellulose
PAC-HV	High Viscosity Polyanionic Cellulose
Pp	Pore Pressure
PSD	Particle Size Distribution
RGC	Resilient Graphitic Carbon
RCC	Regular Cross-Linked Cement
SPA	Sodium Polyacrylates
WBM	Water Base Mud
Yp	Yield Point Viscosity

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II. REAL-TIME LOST CIRCULATION ESTIMATION AND MITIGATION

ABSTRACT

Lost circulation is a challenging problem particularly in the Dammam formation of the Rumaila field, Iraq. Drilling engineers are challenged to select the optimum value for key drilling parameters such as ECD, Yp, MW, WOB, ROP and RPM to mitigate mud losses in this formation. Many of these drilling parameters are inter-related and the overall impact of changing key parameters requires extensive drilling experience or study. A multi-regression analysis was performed on mud loss event data for more than 300 wells drilled in the Dammam formation. From this analysis, a model was developed to predict the total mud losses. Mud loss was found to be significantly affected by MW, ECD and ROP. Models for these key parameters were also developed from multi-regression analysis. The models were confirmed with additional well data from new wells drilled in the field. The models developed in this work provides a method for setting predicted mud losses, then limiting the operational drilling parameters to mitigate such losses in the future wells in fields with similar lithology.

Proactive approaches are made prior entering the Dammam formation to prevent or mitigate the occurrence of the lost circulation. A key drilling parameters are estimated to use during drilling through this formation. In case preventive measures didn’t work, corrective actions are determined for each kind of the mud losses to provide efficient remedies, minimize non-productive time, and reduce cost. The best lost circulation strategy to the Dammam formation is concluded and summarized depending on a comprehensive statistical work, the most important courses of the international oil companies, technical

papers, textbooks, and economic analysis evaluation to determine successful remedies for each type of the losses. These treatments are classified by relying on the mud losses classifications to avoid unwanted consequences due to inappropriate actions. In addition, engineered solutions and practical techniques are developed, which will contribute to give clear image and coherent understanding in regard this complicated and costly problem in the Dammam formation.

1. INTRODUCTION

Drilling fluid losses and problems associated with lost circulation while drilling represent a major expense in drilling oil and gas wells. By industry estimates, more than 2 billion USD is spent annually to combat and mitigate lost circulation (Arshad et al., 2015).

The Rumaila field in Iraq is one of the largest oilfields in the world. Wells drilled in this field are highly susceptible to lost circulation problems when drilling through the Dammam formation. Lost circulation events range from seepage losses to complete loss of the borehole and are a critical issue in field development. Figure 1 shows the Rumaila field location. The Dammam formation is the first formation in the Rumaila field that is prone to mud losses. The top of this zone is found between 450 to 490 m, and all of the wells in the field must be drilled through this formation. The interval is composed of interbedded limestone and dolomite, which is generally 200 to 260 m thick. The top of Dammam was eroded after burial and is karstified at depth. The karst features are believed to lead to the mud losses seen while drilling through this interval. Figure 1 Shows borehole and well construction typical of a well drilled in the Rumaila field at the time the well passes through the Dammam formation. 13-3/8” casing has been set, and most commonly a 12 ¼” bit is used to drill through the formation. A lost circulation event is shown near the bottom of the open hole in Figure 2, but may occur anywhere in the open hole section through the Dammam formation.

Treating the drilling fluid with conventional LCM as background treatments or concentrated pills is a common industry practice to mitigate seepage or partial losses. Other solutions that require more time for preparation and placement are used when severe or complete losses are encountered such as cement (Messenger and McNiel 1952; Messenger

1981; Morita and Fuh 1990; Fidan et al. 2004), chemically activated cross-linked pills (CACP) (Bruton et al. 2001; Caughron et al. 2002), cross-linked cement (Mata and Veiga 2004), deformable-viscous-cohesive systems (DVC) (Whitfill and Wang 2005; Wang et al. 2005, 2008), nanocomposite gel (Lecolier et al. 2005), gunk squeezes (Bruton et al. 2001; Collins et al. 2010), and concentrated sand slurries (Saasen et al. 2004, 2011).

Different testing methods are used to evaluate the performance of LCM treatments, based on the fluid loss volume at a constant pressure, such as the particle plugging apparatus (PPA) or the high-pressure-high-temperature (HPHT) fluid loss in conjunction with slotted/tapered discs or ceramic discs (Whitfill 2008; Kumar and Savari 2011). Other testing equipment has been developed to evaluate the sealing efficiency of LCM treatments in sealing permeable/impermeable fractured formations (Hettema et al. 2007; Sanders et al. 2008; Van Oort et al. 2009). Both particle size distribution (PSD) and total LCM concentration were found to have a significant effect on the sealing efficiency.

This study provides basic information on lost circulation, including an introduction to the problem, identifies a range of factors that affect lost circulation, provide proactive techniques, appropriate corrective actions, and economic evaluation analysis to lost circulation in the Dammam formation. The study summarizes mud loss and lost circulation information extracted from drilling data from the Rumaila field in Iraq. A lost circulation screening criteria are presented for the Rumaila field, based on the historical mud loss and lost circulation problems, materials used to mitigate the problems, and potential solutions found by this study.

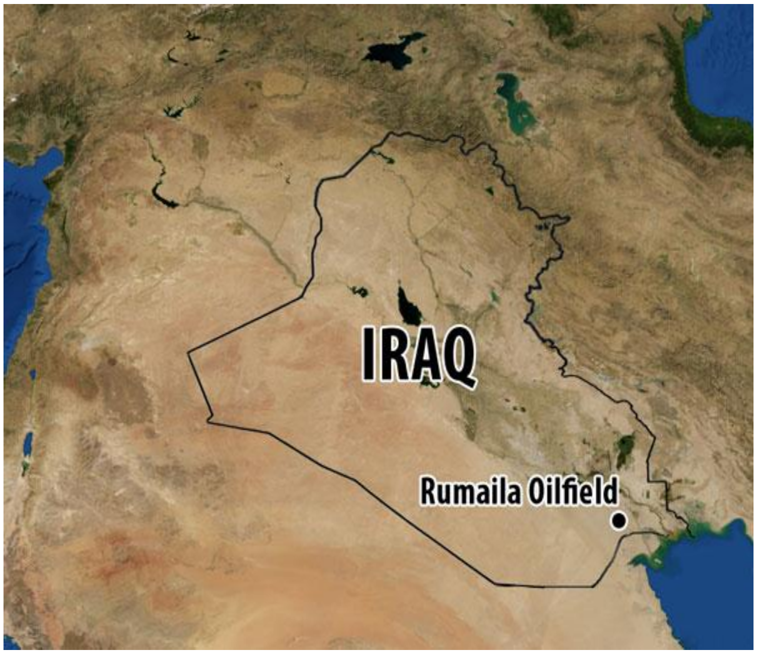


Figure 1. Rumaila Field (www.drillingcontractor.org, 2017)

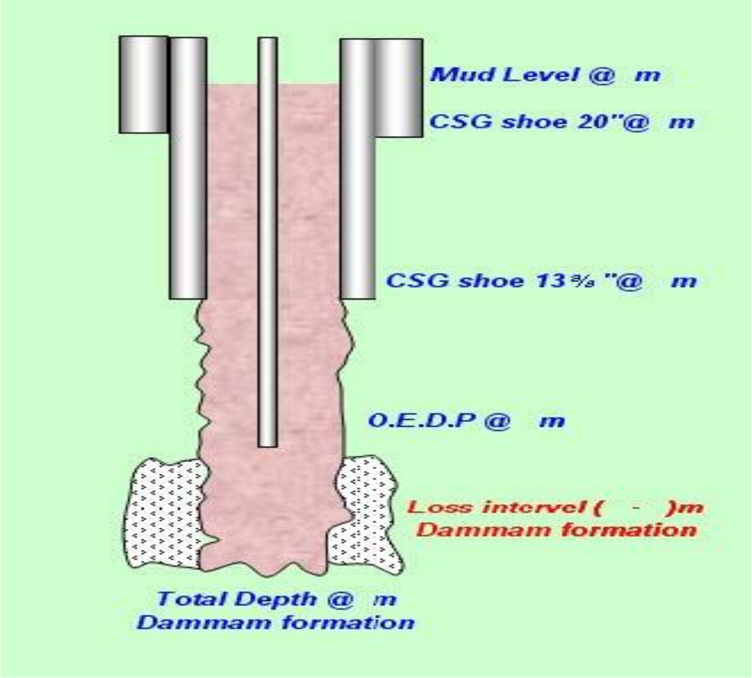


Figure 2. Lost Circulation Mud in the Dammam Formation

2. 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 Dammam formation. The methodology developed is based on analyzing actual mud loss events while drilling the Dammam formation, to develop key statistical models for ROP, ECD, and mud losses. This approach was previously successful in setting drilling parameters in the Shuaiba formation, in the same field (Al-Hameedi, et. al, 2017). However, in that case, the impact of mud type was not considered. For the Dammam formation, the models are also tested with well data differentiated by mud type, Fresh Water Bentonite (FWB) and polymer mud to assess the impact of mud type.

Mud loss events for more than 300 wells drilled in the 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. Table 1 provides example well data used in the study.

JMP Statistical Analysis software was utilized to perform a statistical analysis of the Dammam 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 (Weisberg, 2005). It was necessary to first identify which drilling parameters had the greatest impact on the mud losses. Multi-regression analysis identified that MW 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. A tornado chart was created as a sensitivity analysis, or impact factor, for the major factors influencing the volume loss model, ECD model, and ROP models. 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 (Al-Hameedi, et. al, 2017).

Recommended key drilling parameters have been determined in this paper to prevent or mitigate lost circulation in the Dammam formation, this is done based on reviewing data of key drilling parameters. In addition, mud losses treatments events are examined, and statistical analysis is conducted for these remedies. The probability of each treatment is calculated by adding the number of times they were used successfully divided by the total number of attempts. An economic evaluation is performed for the same data based on the cost of each material and the NPT, the rig cost is estimated to be 36000 $/day. Table 2 shows the prices for lost circulation materials that are used in the economic evaluation (Halliburton, 2016). Thus, lost circulation strategy has been developed by depending on statistical work and economic analysis to efficiently remedy in terms stopping mud losses, minimizing non-productive time, and reducing cost. These treatments strategy has been classified by relying on the type of the lost circulation. Practical field information from a range of sources was reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the Dammam formation (Al-Hameedi, et. al, 2017).

Table 1. Well Data Events, the Dammam Formation

Depth, (m)	MW, (gm/cc)	Yp, (Ibf/100ft^2)	SPM	RPM	Nozzles	Type of losses	Type of Treatment	Result
438 - 512	1.06	12	110	60	WON	No Loss	No Treatment	Success
512 - 562	1.07	20	130	70	WON	Complete Loss	H.V Mud	Fail
562 - 632	/	/	140	75	WON	Complete Loss	Blind Drilling	Success
632	/	/	140	75	No Bit	Complete Loss	Cement Plug	Fail
632	/	/	180	75	No Bit	Complete Loss	H.V Mud + Cement Plug	Success
632 - 668	1.05	14	100	55	WON	No Loss	No Treatment	Success
668 - 704	1.05	14	105	55	WON	No Loss	No Treatment	Success

Table 2. Cost of Lost Circulation Materials

Material Name	Price for each $/Ton	Price for each $/kg
Bentonite	317	0.317
Mica Fine	500	0.5
Mica Medium	700	0.7
Nut Plug	960	0.96
$CaCO_3$ Medium	313	0.313
$CaCO_3$ Coarse	350	0.35
Super Stop Material	1200	1.2
Blend of LCM	900	0.9
Cement	318	0.318
Diesel Oil	500	0.5

3. STATISTICAL MODELS

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 300 wells drilled in the 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 Dammam 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 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.

3.1. VOLUME LOSS 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. As 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 (Analyze-it.com, 2016). 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 3, 4 and 5 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 means that MW, ECD, and Yp statistically significant parameters for overall mud volume losses.

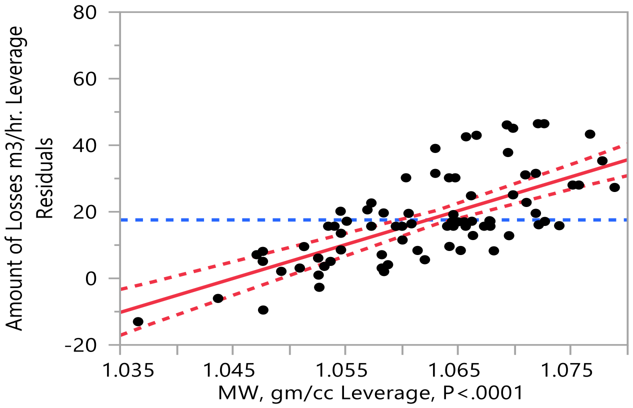


Figure 3. Leverage plot of MW for the Volume Loss Model

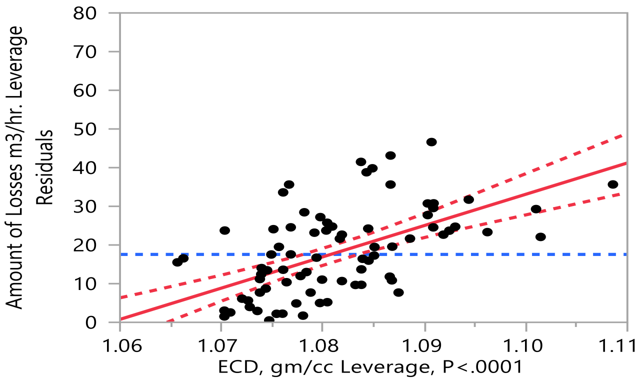


Figure 4. Leverage Plot of ECD for the Volume Loss Model

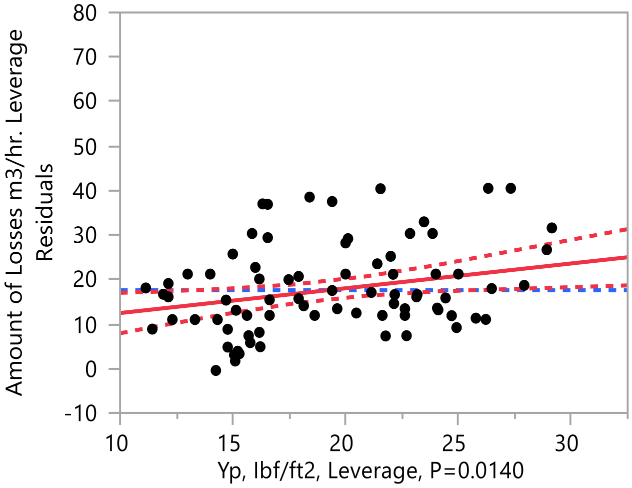


Figure 5. Leverage Plot of Yp for the Volume Loss Model

ECD, MW and Yp were found to be the significant parameters for the volume 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 loss volume before drilling the Dammam formation. The volume loss model developed is expressed by Eq. (1):

$$\text{Mud Losses} = -1950.102 + 1019.371 * \text{MW}\left(\frac{\text{gm}}{\text{cc}}\right) + 808.816 * \text{ECD}\left(\frac{\text{gm}}{\text{cc}}\right) + 0.557 * \text{Yp}\left(\frac{\text{Ibf}}{100\text{ft}^2}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Figure 6 shows the actual versus the predicted mud losses. The R-squared of this model is 0.783; however, the adjusted R-squared is 0.775. 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 (Montgomery, 2001). Since there are multiple independent variables, the adjusted R-squared should be used instead of the R-squared.

Figure 7 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 (Montgomery, 2001). The points in the residual plot are randomly distributed, this confirms that a linear regression model is appropriate for the data.

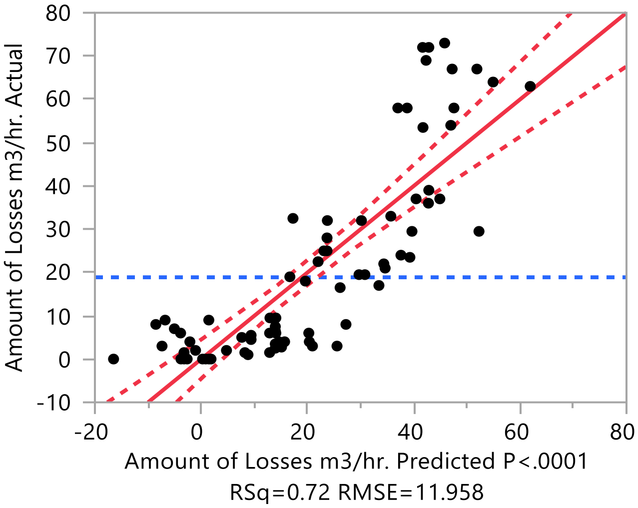


Figure 6. The Actual Versus the Predicted Mud Losses

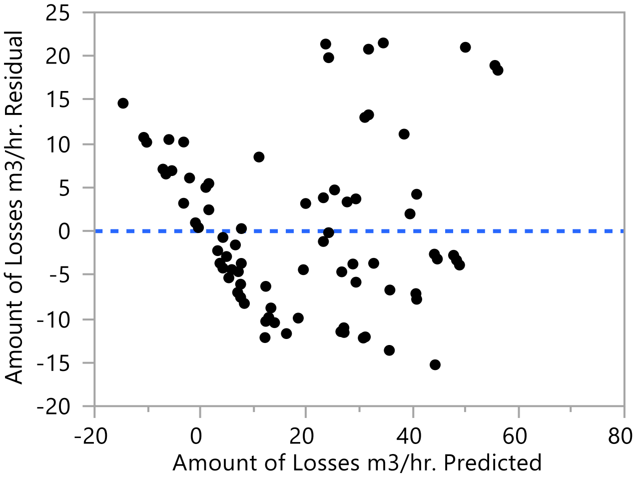


Figure 7. Residual Plot for Volume Loss Model

Collinearity (also known as multicollinearity) refers to the condition where two or more independent variables in a multi-linear regression model are highly correlated (Yan and Su, 2009). 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 (www.stat.tamu.edu, 2017). 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 volume 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 3 shows the summary of the p-values and VIF test. No VIF value exceeded 5. Hence, no multicollinearity is observed in the model.

Table 3. Summary of P-values and VIF Test

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**	**VIF Test**
Intercept	-1950.102	115.9162	-16.82	<.0001	.
MW, gm/cc	1019.3712	121.3025	8.40	<.0001	1.6353261
ECD, gm/cc	808.8164	125.1977	6.46	<.0001	1.6815957
Yp, Ibf/100ft^2	0.5571199	0.221863	2.51	0.0140	1.1575631

Figure 8 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=1.05 g/cc, ECD=1.08 g/cc, and Yp=622.44 Pascal (13Ibf/100ft2). Figure 8 shows the impact of each parameter on the volume loss model. MW, in the order of the magnitude of their influence. The volume loss is least influenced by the Yp as shown in Figure 8, but Yp is a significant parameter and therefore included in the model.

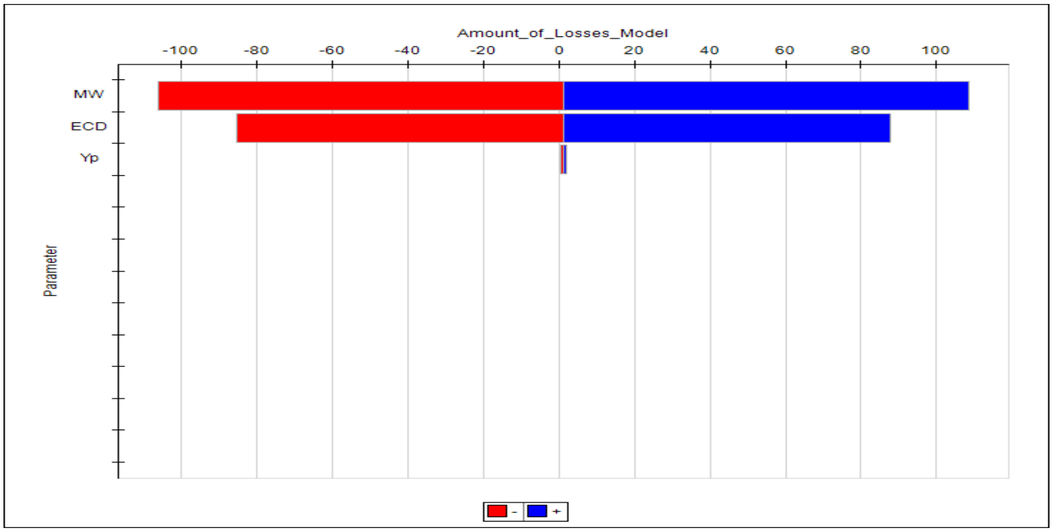


Figure 8. Sensitivity Analysis for the Volume Loss Model

3.2. EQUIVALENT CIRCULATION DENSITY (ECD) MODEL

Using the same approach in the volume loss model, a model for the ECD model has been developed by using a multi-linear regression analysis. 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). 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 Eq. (2):

$$\mathrm{ECD} = 0.8512 + 0.1723 * \mathrm{MW}\left(\frac{\mathrm{gm}}{\mathrm{cc}}\right) + 0.0071 * \mathrm{ROP}\left(\frac{\mathrm{m}}{\mathrm{hr}}\right) - 0.0000026251 * \mathrm{Q}\left(\frac{\mathrm{L}}{\mathrm{min}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

ECD calculated using Equation 2 can be used as an input for Equation 1 (the volume loss model). ECD is a parameter that can be found during the drilling operation only. Eq. (2) provides a good estimation for ECD in the Dammam formation. More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017).

3.3. RATE OF PENETRATION (ROP) MODEL

After performing the multi-regression analysis, three parameters, including RPM, SPM and WOB were found to be significant. 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 Dammam formation can be estimated using RPM, SPM, and WOB. The ROP model can be expressed using Eq. (3):

$$\mathrm{ROP} = 1.972 + 0.00648 * \mathrm{SPM} + 0.00642 * \mathrm{RPM} + 0.462 * \mathrm{WOB}\ (\mathrm{Ton}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Eq. (3) gives a good estimation for the ROP in the Dammam formation. In addition, the results of Eq. (3) can be used as an input for Eq. (2) (ECD model). More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017).

4. 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 Dammam formation. The three models developed in the research can be combined to achieve this aim. Mud volume losses can be predicted for the Dammam 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. 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 Dammam formation.

It is important to validate the models prior to field use. Hence, additional the Dammam mud loss events data was collected to test each model, predicted value (the mud loss, ECD, ROP) against the actual, new data. Table 4 and 5 summarize the number of mud loss events in new wells mud loss events compared to the original events used in the model development for two types of muds which are polymer mud and FWB. Table 4 and 5 show the mud loss events count for original wells used to develop the models and wells used for testing model results. In addition, Figures 9 – 14 are plots of predicted values of ROP, ECD and the volume loss plotted against actual data, respectively, and all six figures are for partial losses. There is a strong correlation between predicted and actual for all ROP, ECD, and losses models results.

Table 4. Summary of the Application of the Real Filed Data, Polymer Mud

Type of the Losses	New Wells	Old Wells	Total New Wells	Total Old Wells	Total Wells
Partial Losses	26	12	65	32	97
Severe and Complete Losses	39	20			

Table 5. Summary of the Application of the Real Filed Data, FWB Mud

Type of the Losses	New Wells	Old Wells	Total New Wells	Total Old Wells	Total Wells
Partial Losses	21	13	63	24	87
Severe and Complete Losses	42	11			

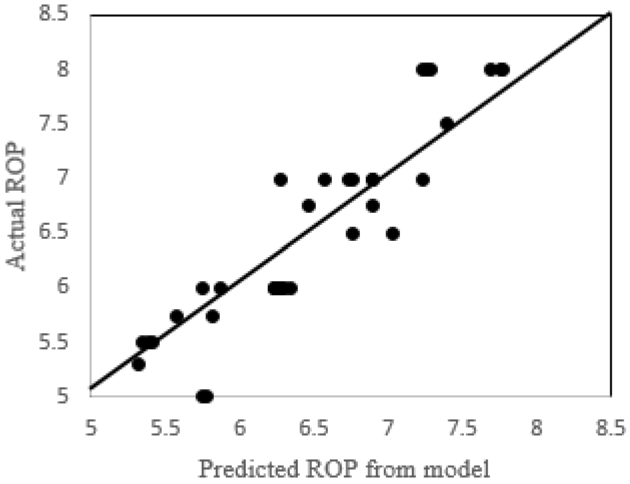


Figure 9. Actual vs. Predicted ROP for Partial Losses (FWB Mud)

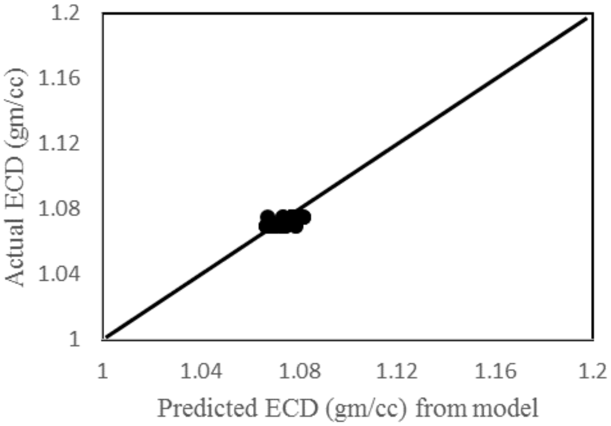


Figure 10. Actual vs. Predicted ECD for Partial Losses (FWB Mud)

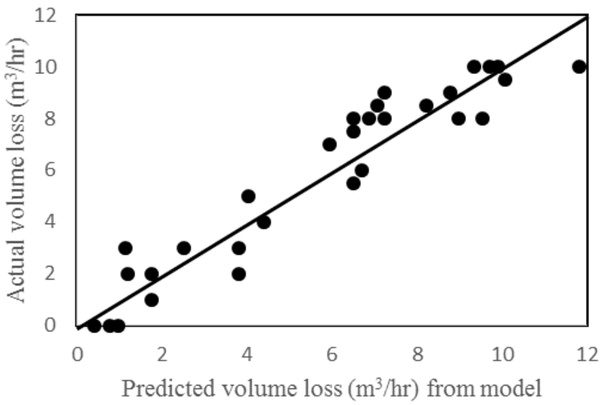


Figure 11. Actual vs. Predicted Volume Loss for Partial Losses (FWB Mud)

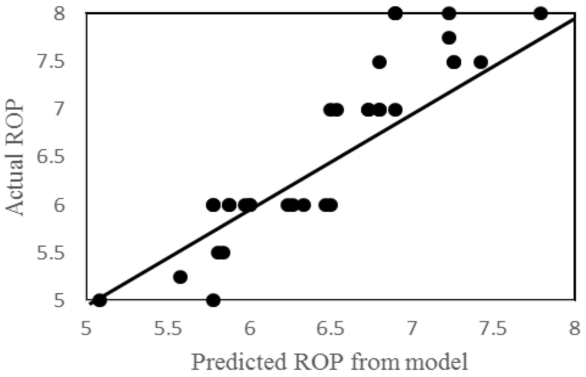


Figure 12 Actual vs. Predicted ROP for Partial Losses (Pol.M)

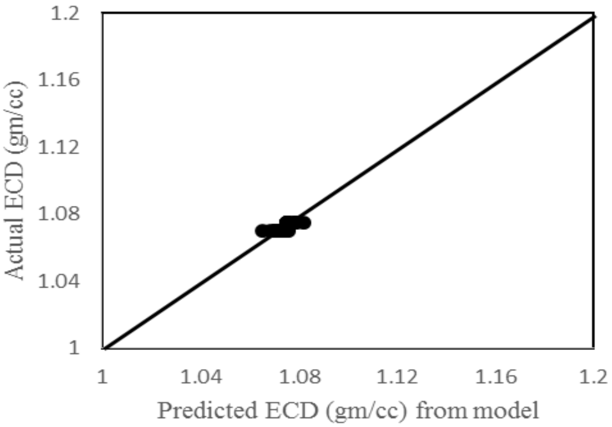


Figure 13. Actual vs. Predicted ECD for Partial Losses (Pol.M)

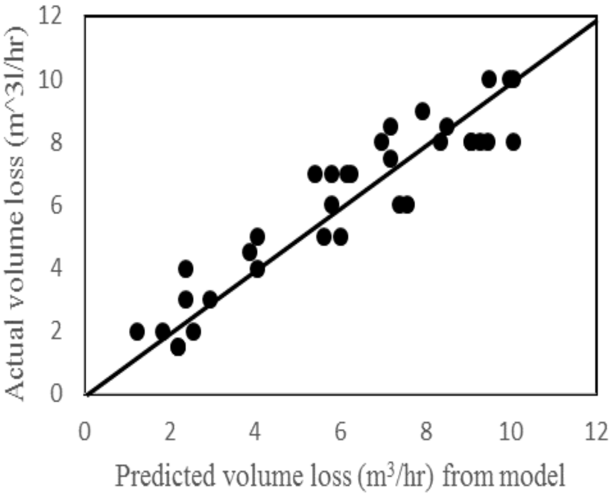


Figure 14. Actual Vs. Predicted Volume Loss for Partial Losses (Pol.M)

Figures 15-20 are plots of predicted values of ROP, ECD and the volume loss plotted against actual data, respectively, and all six figures are for severe and complete losses. There is a strong correlation between predicted and actual for all ROP, ECD, and losses models results.

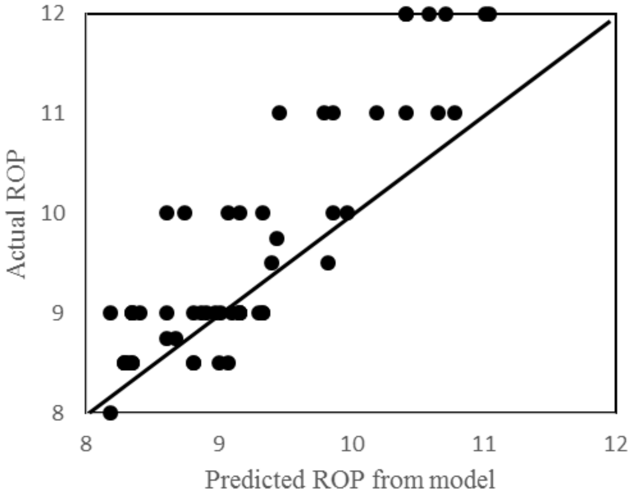


Figure 15. Actual Vs. Predicted ROP for Severe and Complete Losses (FWB Mud)

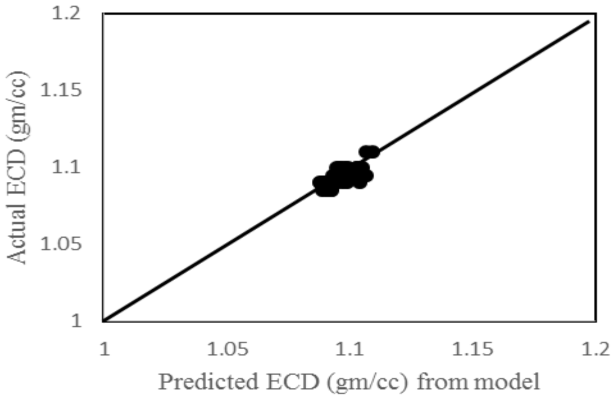


Figure 16. Actual vs. Predicted ECD for Severe and Complete Losses (FWBM)

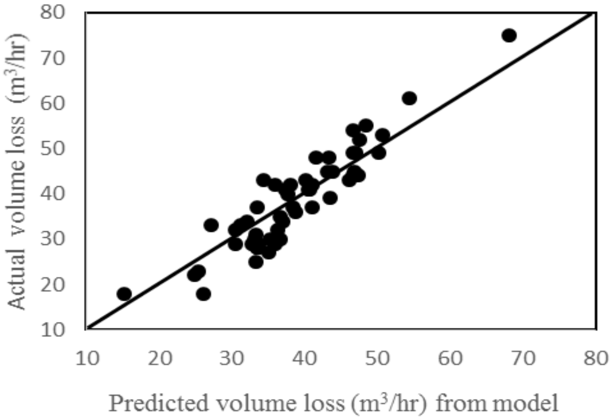


Figure 17. Actual vs. Predicted Volume Loss for Severe and Complete Losses

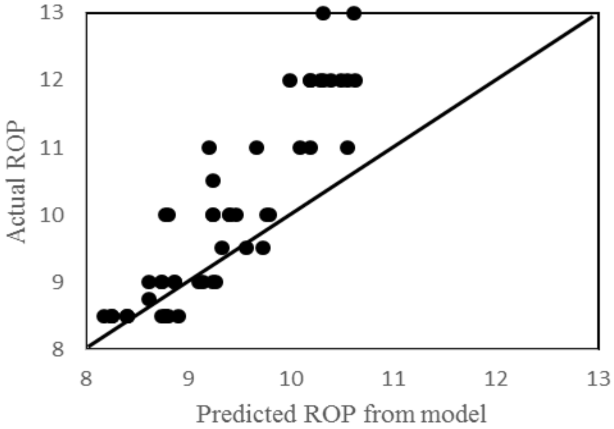


Figure 18. Actual vs. Predicted ROP for Severe and Complete Losses (Pol.M)

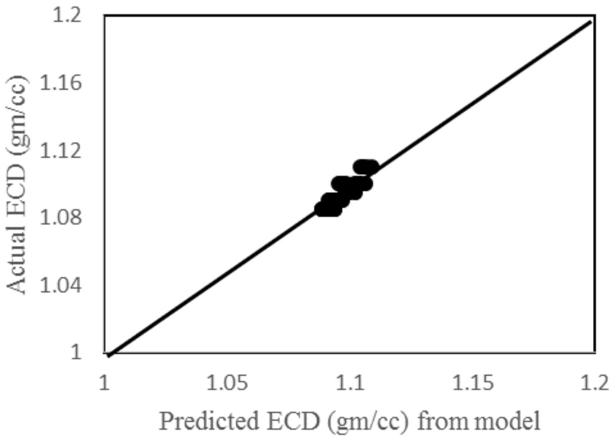


Figure 19. Actual vs. Predicted ECD for Severe and Complete Losses (Pol.M)

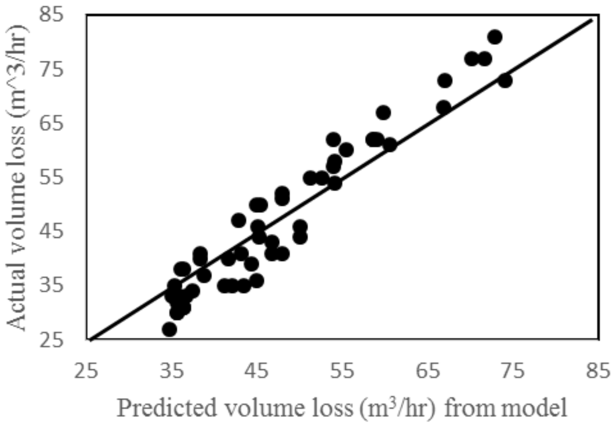


Figure 20. Actual Vs. Predicted Volume Loss for Severe and Complete Losses

5. RECOMMENDED KEY DRILLING PARAMETERS TO DRILL THE DAMMAM FORMATION (PREVENTIVE APPROACHES)

Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al., 2005). All those remedies/techniques that are applied prior to entering lost circulation zones to prevent the occurrence of losses can be defined as proactive methods. The main advantage of using these techniques are to increase the chances of avoiding or minimizing lost circulation in the Dammam formation. Many methods are used to mitigate mud loss prior to entering the lost circulation zone. Some examples of these methods are waiting method, reduction of pump rate, reduction of mud weight, increase drilling fluid viscosity, and using bit without nozzles. On this study, the best ranges of key drilling parameters to drill the Dammam formation are identified and summarized by reviewing historical data, integrated analysis, and comprehensive statistical study. As a proactive approach, each key drilling parameter is analyzed separately to estimate the best operational range that will prevent or mitigate mud losses. Figures 21-31 are plots of estimated the best range of key drilling parameters. Table 6 shows recommended key drilling parameters to drill the Dammam formation.

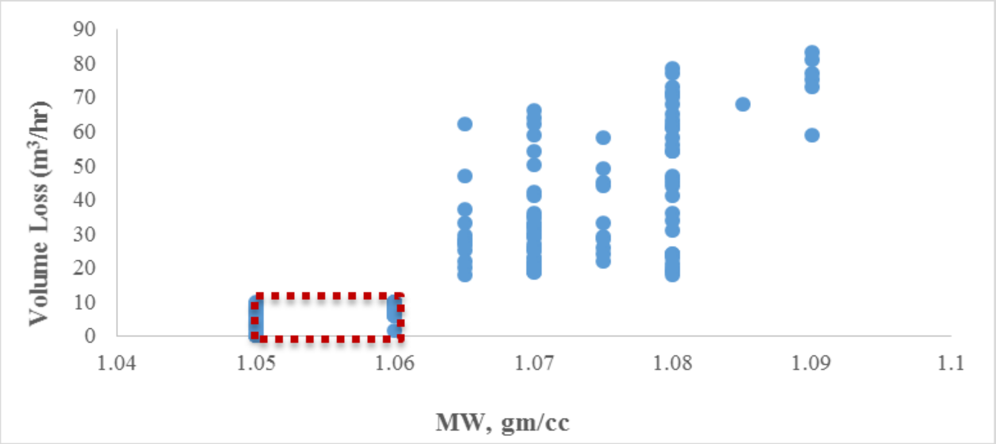


Figure 21. MW versus Volume Loss (more than 300 Wells)

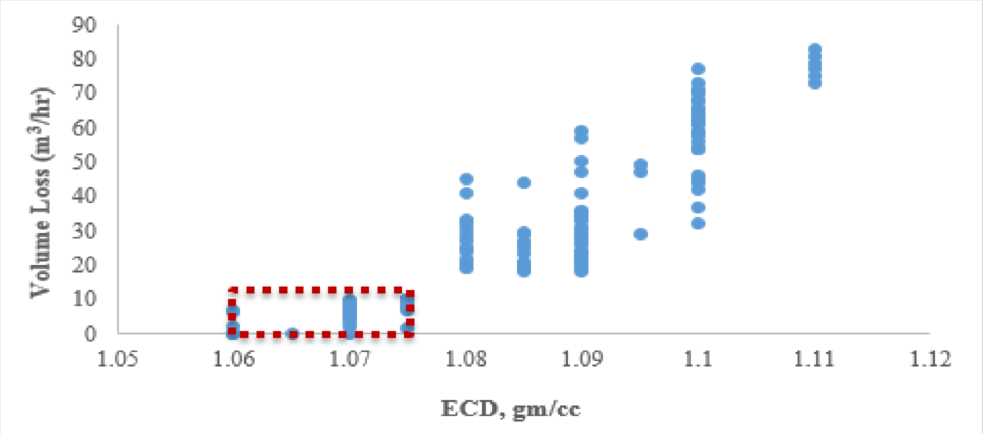


Figure 22. ECD versus Volume Loss (more than 300 Wells)

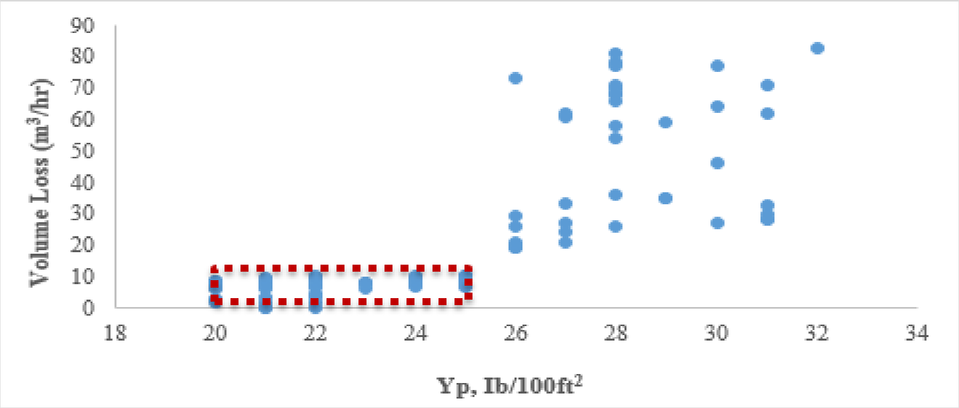


Figure 23. Yp versus Volume Loss (Polymer Mud, more than 300 Wells)

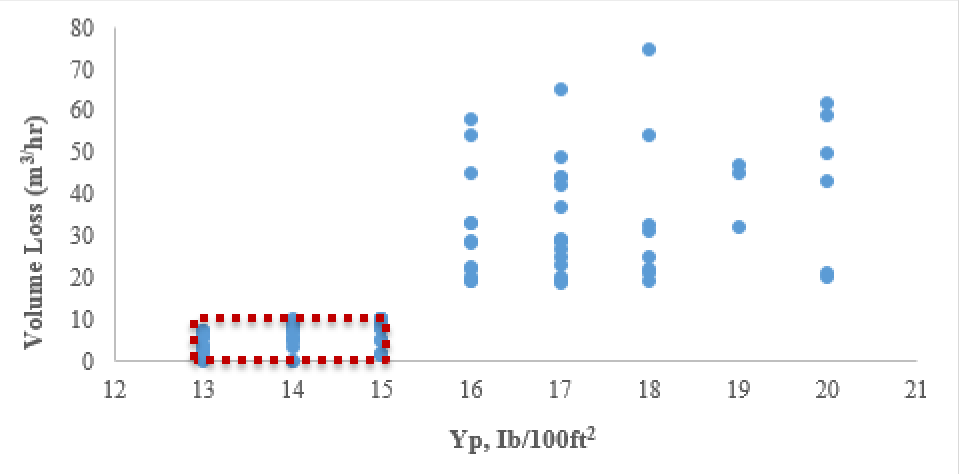


Figure 24. Yp versus Volume Loss (FWB mud, more than 300 Wells)

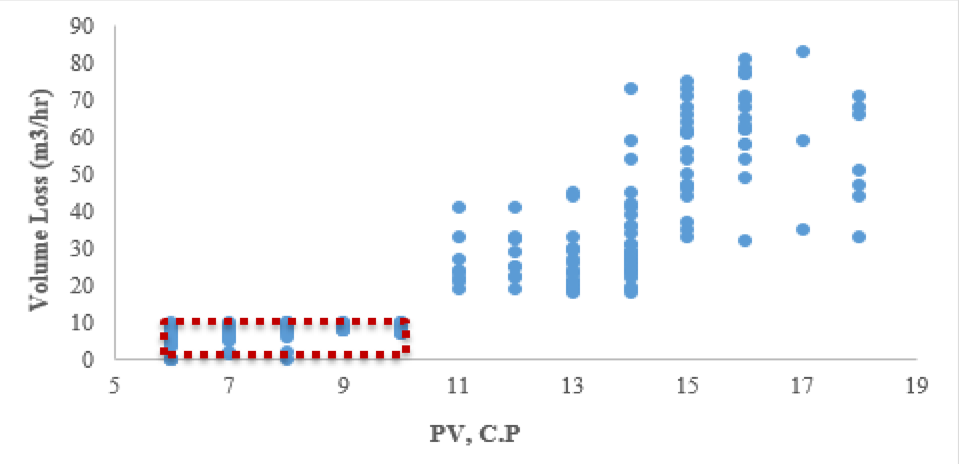


Figure 25. PV versus Volume Loss (more than 300 Wells)

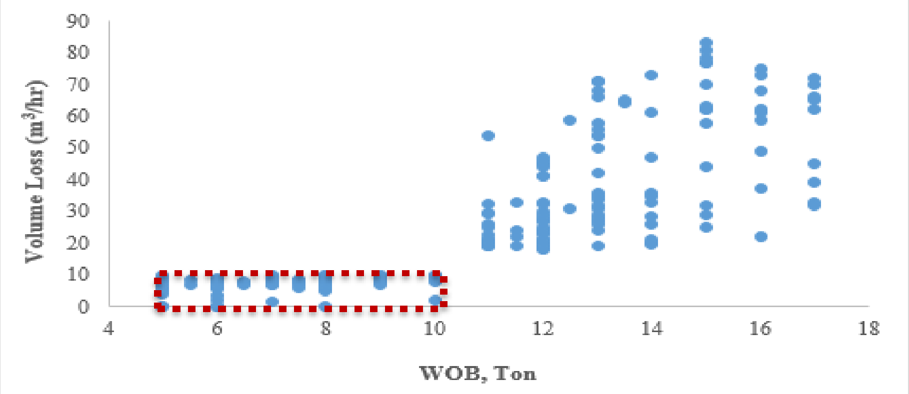


Figure 26. WOB versus Volume Loss (more than 300 Wells)

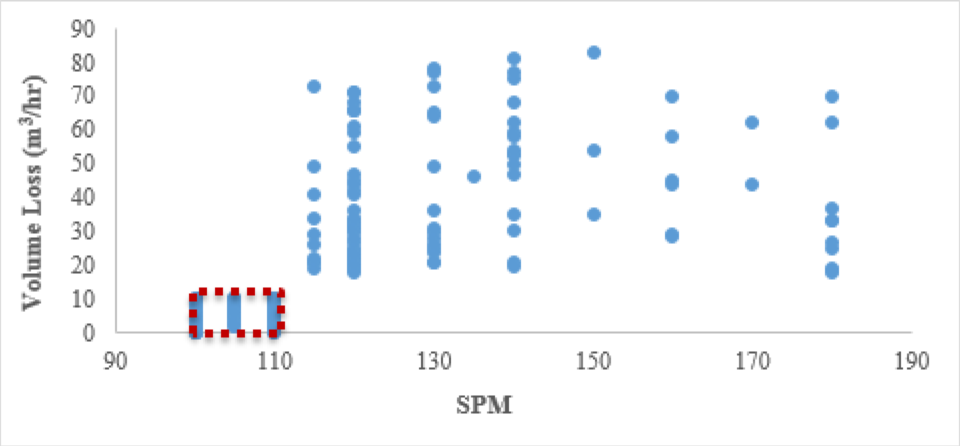


Figure 27. SPM versus Volume Loss (more than 300 Wells)

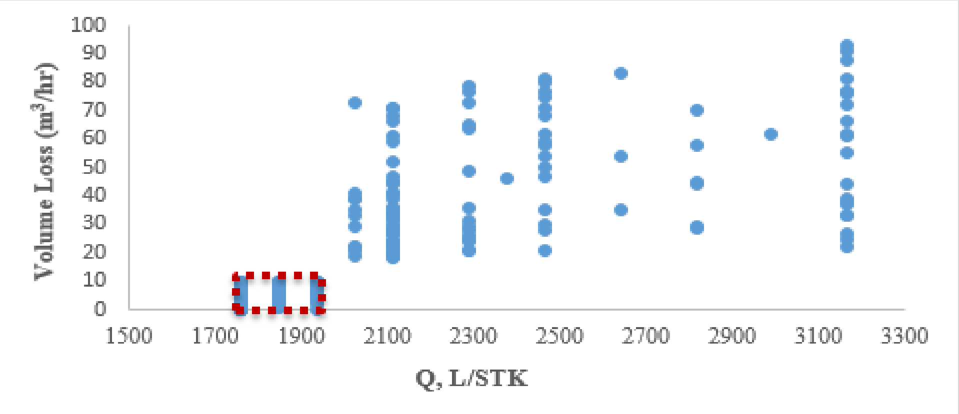


Figure 28. Q versus Volume Loss (more than 300 Wells)

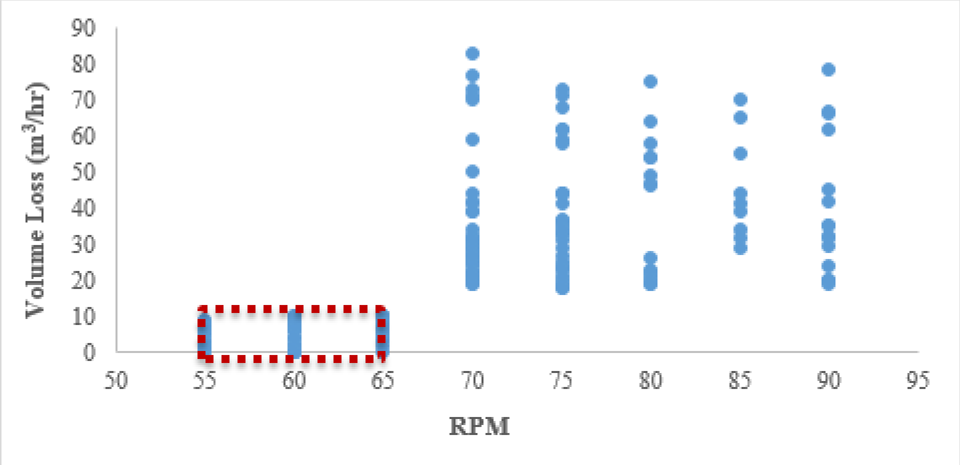


Figure 29. RPM versus Volume Loss (more than 300 Wells)

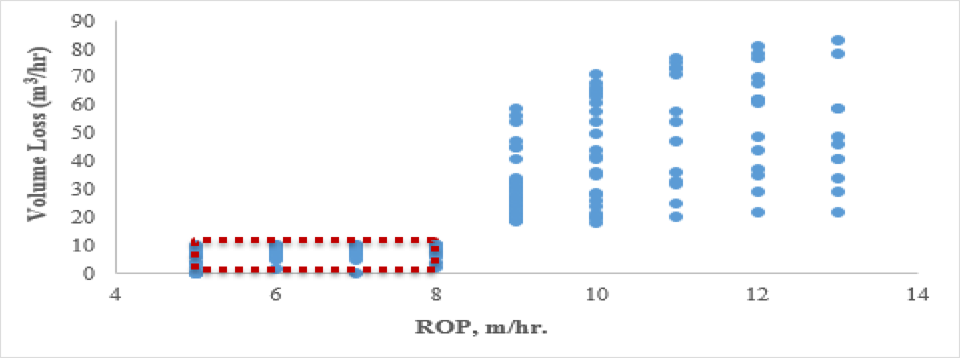


Figure 30. ROP versus Volume Loss (more than 300 Wells)

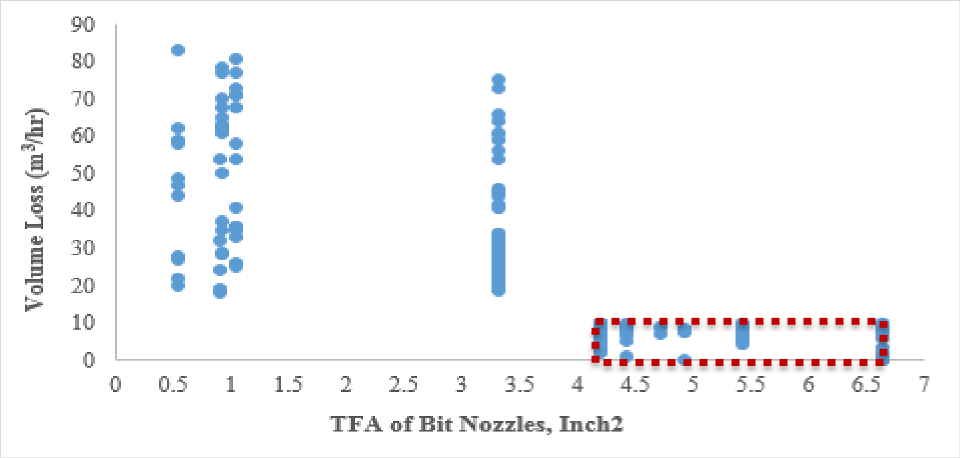


Figure 31. TFA versus Volume Loss (more than 300 Wells)

Table 6. Recommended Key Drilling Parameters for the Dammam Formation

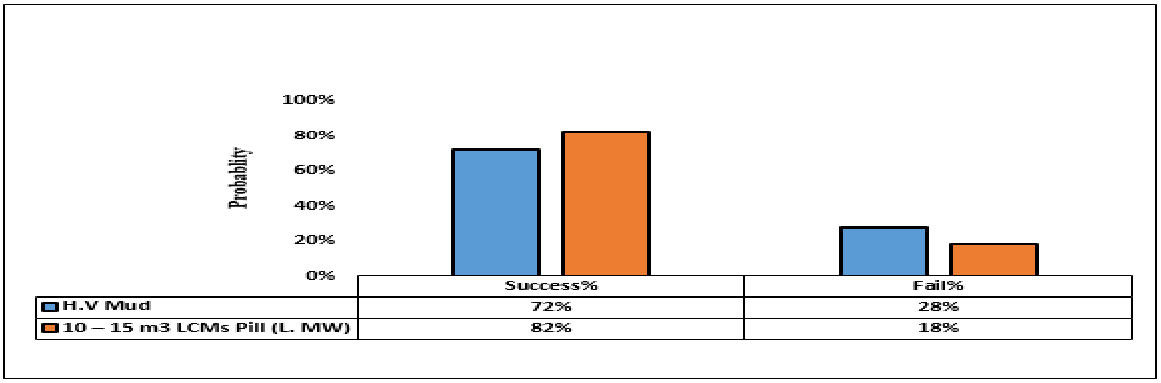
Property	**Minimum Value**	**Maximum Value**
Mud Weight (MW, gm/cc),	1.05	1.06
Equivalent Circulation Density (ECD), (gm/cc)	1.06	1.075
Yield Point (Yp), (Ibf/100ft^2) (Polymer Mud)	20	25
Yield Point (Yp), (Ibf/100ft^2) (FWB Mud)	13	15
Plastic Viscosity (PV), cp	6	10
Weight of Bit (WOB), Ton	5	10
Strokes per Minute (SPM)	100	110
Flow Rate (Q), L/STK	1760	1936
Revolutions per Minute (RPM)	55	65
Rate of Penetration (ROP, m/hr.)	5	8
Bit Nozzles	Without Nozzles	Without Nozzles

6. RECOMMENDED LOST CIRCULATION STRATEGY TO THE DAMMAM FORMATION (CORRECTIVE METHODS)

In case the preventive measures didn’t work, remedial treatments should be used to stop the mud losses. Hence, it is recognized that there is no single solution to lost circulation, and that most treatment and trial-and-error. However, the screening guide presents a high-level ‘go to’ document with coherent guidelines, which engineers can utilize in making decisions regarding lost circulation treatments in the Dammam formation. The part also employed a thorough literature review to identify relevant information that could be included in developing the screening guide.

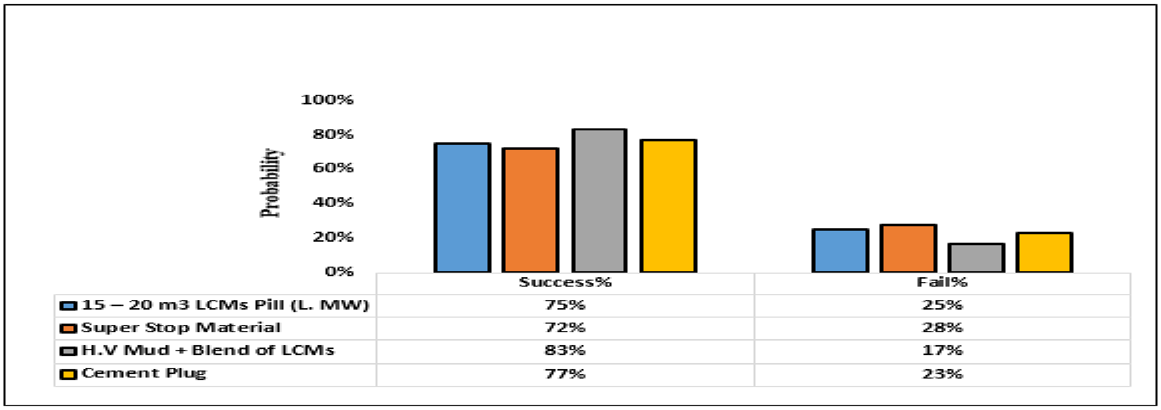
This section will summarize the required treatments for each type of the lost circulation. Figures 32 to 34 are presented the remedies for partial, severe, and complete losses that were used in the Rumaila field. Selecting appropriate treatment by depending on the type of the lost circulation, which will reflect positively on the drilling operations in terms combating the problem, saving time, and reducing expenses. More than 300 wells have been analyzed to figure out the successful remedies for each type of the losses, and these treatments are classified by relying on the mud losses classifications to get effective remedies, minimize cost, reduce non-productive time, and avoid unwanted consequences due to inappropriate actions. A lost circulation screening criteria is presented for this formation based on the historical mud loss and lost circulation problems, materials used to mitigate the problems, and potential solutions found by this study.

The economic evaluation is conducted for partial, severe, and complete losses. Table 7 to 9 show the results of the economic evaluation for the best partial, sever, and complete losses treatments with their probabilities.



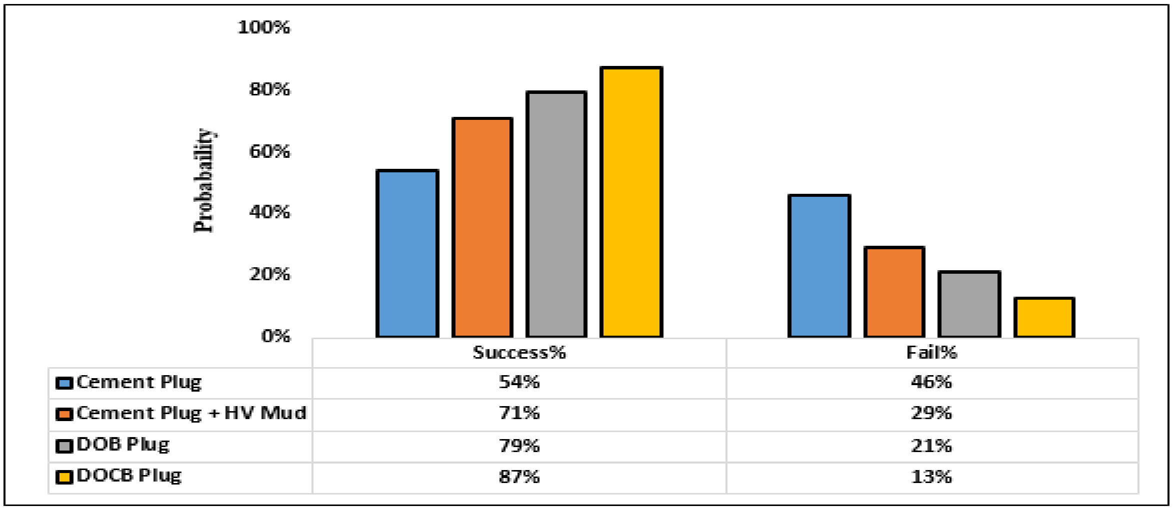
	Success%	Fail%
🟦 H.V Mud	72%	28%
🟧 10 – 15 m3 LCMs Pill (L. MW)	82%	18%

Figure 32. Recommended Remedies for Partial Losses (more than 300 Wells)



	Success%	Fail%
🟦 15 – 20 m3 LCMs Pill (L. MW)	75%	25%
🟧 Super Stop Material	72%	28%
▨ H.V Mud + Blend of LCMs	83%	17%
🟨 Cement Plug	77%	23%

Figure 33. Recommended Remedies for Severe Losses (more than 300 Wells)



	Success%	Fail%
🟦 Cement Plug	54%	46%
🟧 Cement Plug + HV Mud	71%	29%
▨ DOB Plug	79%	21%
🟨 DOCB Plug	87%	13%

Figure 34. Recommended Remedies for Complete Losses (more than 300 Wells)

Table 7. Partial Losses Economic Calculations and Probabilities

Treatment Name	Required Addition, kg/m^3	Cost, \$/m^3	Waiting Period, (hrs.)	NPT Cost, \$/1hr	Total Cost, (\$)	Success%	Failure%
H.V Mud Patch	100	31.7	2.5	1500	3781.7	72	28
Pill of LCM	Mica Fine (15), Mica Medium (15), Nut Plug (15), $CaCO_3$ Medium (15), $CaCO_3$ Coarse (15)	42.345	3.5	1500	5292.34	82	18

Table 8. Severe Losses Economic Calculations and Probabilities

Treatment Name	Required Addition, kg/m^3	Cost, \$/m^3	Waiting Period, (hrs.)	NPT Cost, \$/1hr	Total Cost, (\$)	Success %	Failure %
Pill of LCM	Mica Fine (30), Mica Medium (30), Nut Plug (30), $CaCO_3$ Medium (30), $CaCO_3$ Coarse (30)	84.69	3.5	1500	5334.69	75	25
Super Stop Material	125	150	4.5	1500	6900	72	28
H.V Mud + Blend of LCM	Bentonite (100), Blend LCM (45)	72.2	5	1500	7572.2	83	17
Cement Plug	1029	327.22	18	1500	27327	77	23

Table 9. Complete Losses Economic Calculations and Probabilities

Treatment Name	Required Addition, kg/m^3	Cost, \$/m^3	Waiting Period, (hrs.)	NPT Cost, \$/1hr	Total Cost, (\$)	Success %	Failure %
Cement Plug	1029	327	18	1500	27327	54	46
H.V Mud +Cement Plug	Bentonite (100), Cement (1029)	358.92	20	1500	30358.9	71	29
DOB Plug	Formula for 1 m^3 Oil base 0.70 m^3 Bentonite 800 kg	603.6	10	1500	15603.6	79	21
DOBC Plug	Formula for 1 m^3 Oil base 0.72 m^3 Bentonite 450 kg Cement 450 kg	645.75	12	1500	18645.7	87	13

Figure 35 provides guidance for drilling through the Dammam formation and handling loss circulation through this formation. Lost Circulation Strategy to the Dammam formation will be organized depending on the efficiency of the remedy (high probability of success) for several reasons:

1. To maximize the guarantee of the treatment success.
2. To avoid or reduce repetition of the treatments that use to stop lost circulation.
3. To minimize NPT by using appropriate actions.
4. To acquire more effectively cost. In different words, using corrective measures that are associated with high success percentage are more economic than applying remedial actions that have low success percentage.

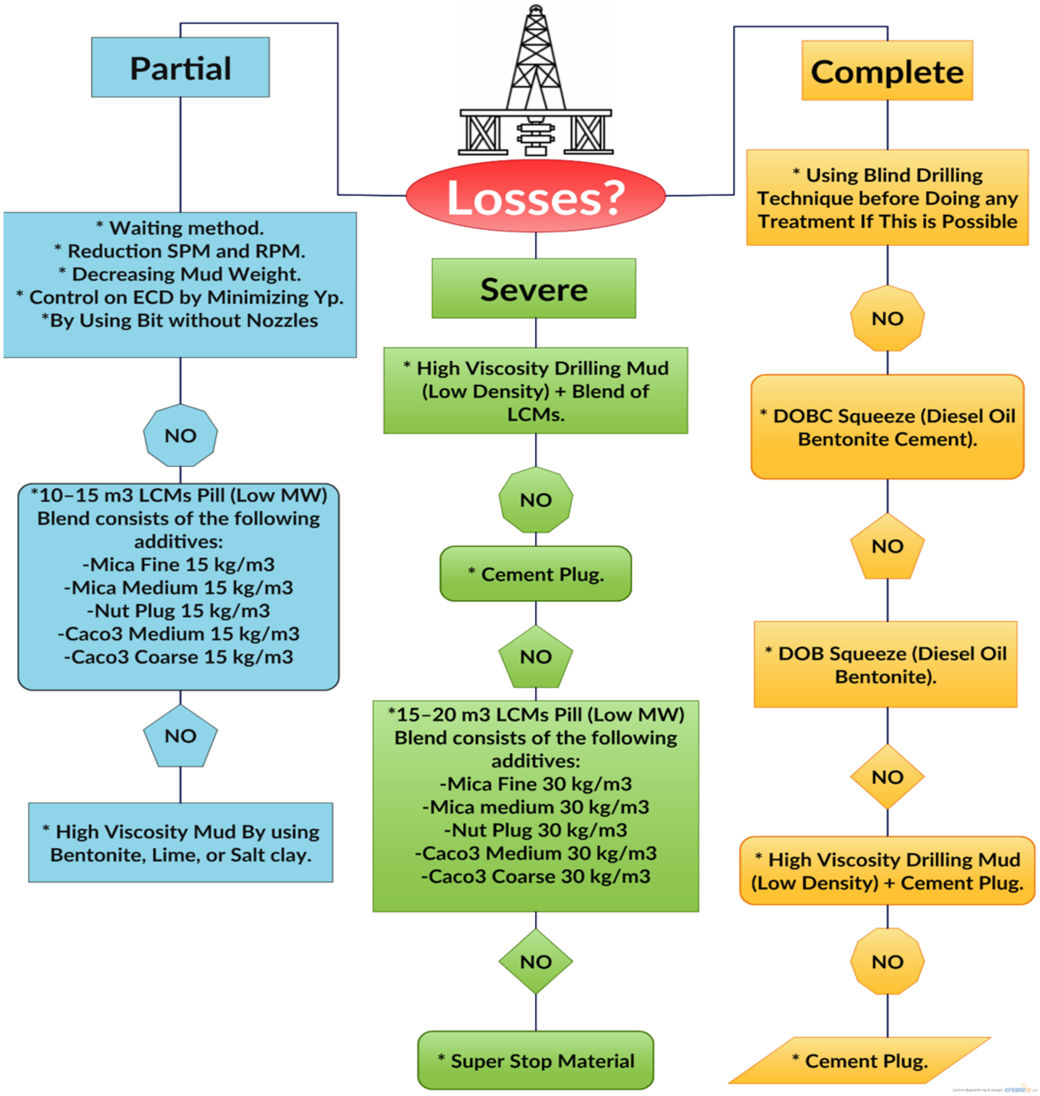


Figure 35. The Best Treatment Strategy to the Dammam Formation

7. GENERALIZATION OF THE VOLUME LOSS MODEL FOR THE DAMMAM FORMATION

The above three statistical models have been generalized to come up with one equation for Dammam formation (only volume loss equation) to predict the mud losses anywhere in Basra's oil fields. ROP model (Equation 3) has been substituted in ECD model (Equation 2), and then ECD model has been substituted in volume loss model (Equation 1), Figure 36 illustrates the implemented procedures for the generalization of volume loss model.

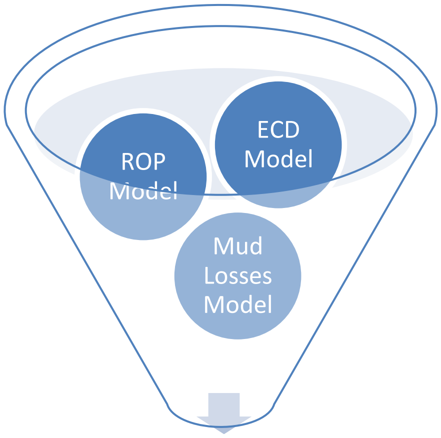


Figure 36. Generalization of Volume Loss Model for the Dammam Formation

Based on MW, Q, RPM, WOB, and Yp a model to estimate the volume loss was developed to estimate the loss volume before drilling the Dammam formation in Basra's oil fields. The volume loss model developed is expressed by Eq. (4):

$$\text{Mud Losses} = -1250.31 + 1158.73 * MW - .000009 * Q + 0.036867 * RPM + 2.65308 * WOB + 0.557 * Yp \quad (4)$$

8. CONCLUSION

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 300 wells drilled in the 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 mud losses, ECD, and ROP.

The three models developed in this study can be used to estimate expected of the mud losses prior to drilling the Dammam 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 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.

In addition, this paper provides a detailed study of lost circulation, including a brief review of fundamentals of lost circulation, analyzing real field data, discussion of methods of mitigating losses, and an introduction to newer methods of loss control used in industry. Lost circulation presents many challenges in the drilling operations. To address these problems, a number of methods/techniques have evolved over the years. The solutions are therefore grouped into preventive and remedial respectively.

Based on this study, the following conclusion are made:

1. Key drilling parameters that should be used to drill the Dammam formation are identified and summarized in Table 6, lost circulation can be avoided or mitigated when using these parameters.

2. Treatments for partial, severe, and complete losses for the Dammam formation are summarized in a flow chart. This flow chart should be used to treat the mud losses in the Dammam formation depending on the type of mud losses.
3. The highest probability of success treatment should be used to treat the mud losses even if it is not the cheapest to avoid the repetition of treatments which reduces the NPT. Using a low-probability of success treatment may not be effective, and the usage of multiple treatments may be required, even if it is cheaper than other treatment, but the NPT will be higher which increases the cost.
4. The first treatment that should be used to treat partial losses is the waiting method. If it fails, then use the recommended treatments in the flow chart.
5. The first treatment that should be used to treat severe losses is high viscosity mud and blend of LCM. If it fails, then use the recommended treatments in the flow chart.
6. The best treatment to begin with the complete losses is DOBC. This treatment is not easy to be performed in the field. Thus, mud crew should be trained to perform this treatment correctly and to maximize the success of the treatment.
7. It is not easy to find guaranteed methods which entirely control or solve lost circulation problems. However, there are some techniques and approaches can be used to prevent its occurrence.

NOMENCLATURE

Symbol	**Description**
D	Depth
DDR	Daily Drilling Report
DOH	Diameter of Open Hole
ECD	Equivalent Circulation Density
FP	Fracture Pressure
Ft/min	foot per minute
FWB	Fresh Water Bentonite
gm/cc	gram per cubed centimeter
HP	Hydrostatic Pressure
H. V	High Viscosity
Ib/bbl	pounds per barrel
Ib/ft^3	pounds per cubed feet
in	Inch
Kg/m^3	Kilogram per cubed meter
LCMs	Lost Circulation Materials
L/min	Litter per minute
m	meter
m^3/hr	cubed meter per hour
MW	Mud Weight
NPT	Non-productive Time

O.E.D.P	Open End Drill Pressure
ppg	pounds per gallon
PP	Pore Pressure
Q	Flow Rate
ROP	Rate of Penetration
RPM	Revolutions per Minute
SPM	Stroke per Minute
TFA	Total Flow Area
WOB	Weight of Bit
WOC	Waiting of Cement
WON	Without Nozzles
Yp	Yield Point Viscosity
$	Dollar

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III. BIG DATA ANALYSIS IDENTIFIES EFFECTIVE LOST CIRCULATION SOLUTIONS IN THE HARTHA FORMATION

ABSTRACT

Wells drilled in Rumaila field are highly susceptible to lost circulation problems when drilling through the Hartha formation. This paper presents an extended statistical work and sensitivity analysis models of lost circulation events in more than 300 wells drilled in Rumaila field. Lost circulation data are extracted from daily drilling reports, final reports, and technical reports. The volume loss model is conducted to predict the mud losses in the Hartha formation. Observations that are made from the volume loss model are ECD, MW, and Yp have a significant impact on lost circulation respectively; however, SPM, RPM, and ROP have a minor effect on the mud losses. Equivalent circulation density model is obtained to estimate ECD in the Hartha zone, and from this model can be deduced that MW, ROP, and Q have a significant impact on ECD respectively; nevertheless, RPM and Yp have a minor impact on the ECD. The rate of penetration model is made to estimate ROP in the Hatha zone. It is concluded that WOB, RPM, and SPM have a significant impact on the ROP respectively. Due to the lack of published studies for the Hartha formation, this work can serve as a practical resource for drilling through this formation.

Practical field information from the Rumaila field and range of sources have been reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in this formation. In a related development, this paper will be extended work along with previous comprehensive statistical study and sensitivity analysis models about other formations to obtain the best field procedures for avoiding or minimizing lost circulation events in the Hartha formation. Proactive approaches have been

made prior entering the Hartha formation to prevent or mitigate the occurrence of lost circulation in the Hartha formation. In case, preventive methods didn’t work, corrective actions have been determined for each kind of the mud losses to provide effective remedies, minimize non-productive time, and reduce cost.

This study provides a typical compilation of information regarding traditional approaches and the latest approaches to lost circulation control. In addition, the work attempts to provide useful guidelines or references for both situations in terms preventive measures, remedial methods, and analytical economic study.

1. INTRODUCTION

Lost circulation problems may occur from shallow, unconsolidated formations to deeper, consolidated formations as a result of fracturing of the wellbore wall from high pressure applied by the drilling mud (Moore, 1986). The industry spends millions of dollars every year to combat lost circulation, and its associated detrimental effects such as non-productive time (NPT) on the rig, stuck pipe, blow-outs, and less frequently, the abandonment of expensive wells.

This paper shows the application of develop a model for mud loss volumes within the Hartha formation in the Rumaila field in Iraq. The resulting model is compared to models developed for the Dammam and Shuaiba formations in the same field (Al-Hameedi, et. al, 2017). The study summarizes mud loss and lost circulation information extracted from drilling data from the Hartha formation and the lost circulation screening criteria developed for this formation, based on the historical mud loss and lost circulation problems. Three mathematical models have been created to prevent or mitigate the problems, and potential solutions found by this study. Figure 1 shows the borehole and well construction typical of a well drilled in the Rumaila field at the time the well passes through the Hartha formation.

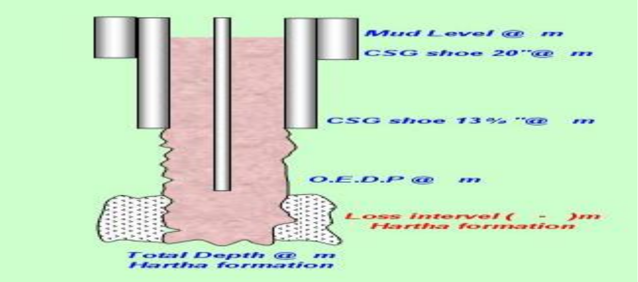

Figure 1. Lost Circulation in the Hartha Formation

2. METHODOLOGY

The purpose of this work was to develop a more systematic approach to determining the best values for these parameters while drilling the Hartha formation. The methodology developed is based on analyzing actual mud loss events while drilling the Hartha formation, to develop key statistical models for ROP, ECD, and mud losses. These models are then tested with other Hartha 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 300 wells drilled in the 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.

JMP Statistical Analysis software was used to perform a statistical analysis of the Hartha 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 (Weisberg, 2005). 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.

Recommended key drilling parameters have been determined in this paper to prevent or mitigate lost circulation in the Hartha formation. This is done based on reviewing data of key drilling parameters. In addition, mud losses treatments events are examined, and statistical analysis is conducted for these remedies. The probability of each treatment is calculated by adding the number of times they were used successfully divided by the total number of attempts. An economic evaluation is performed for the same data based on the cost of each material and the NPT, the rig cost is estimated to be 36000 $/day. Table 1 shows the prices for lost circulation materials that are used in the economic evaluation (Basra Oil Company, 2018). Thus, the lost circulation strategy has been developed by depending on statistical work and economic analysis to efficiently combat in terms stopping mud losses, minimizing non-productive time, and reducing cost, and this treatment strategy has been classified based on type of mud loss.

Table 1. Cost of Lost Circulation Materials

Material Name	Price for each $/Ton	Price for each $/kg
Bentonite	317	0.317
Mica Fine	500	0.5
Mica Medium	700	0.7
Nut Plug	960	0.96
$CaCO_3$ Medium	313	0.313
$CaCO_3$ Coarse	350	0.35
Super Stop Material	1200	1.2
Blend of LCM	900	0.9
Cement	318	0.318

3. STATISTICAL MODELS

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 300 wells drilled in the 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 Hartha 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 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.

3.1. VOLUME LOSS 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. As 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 (Analyze-it.com, 2016). 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 2 is only example to show the leverage plot for MW. 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 means that MW, ECD, and Yp statistically significant parameters for overall mud volume losses.

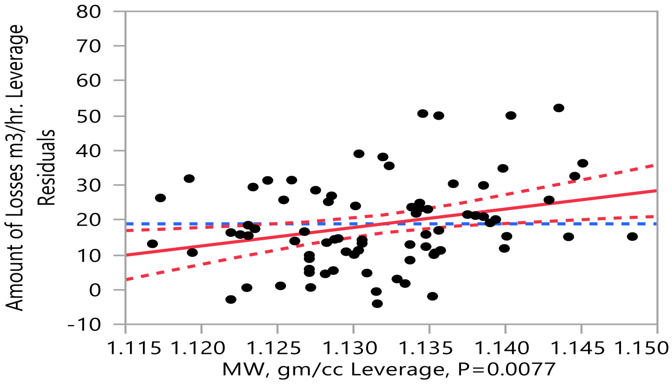

Figure 2. Leverage Plot of MW for the Amount of Losses Model

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 Hartha formation. The amount of the loss model expressed by Equation 1:

$$\text{Mud Losses} = -1915.757 + 530.782 * \text{MW}\left(\frac{\text{gm}}{\text{cc}}\right) + 1144.376 * \text{ECD}\left(\frac{\text{gm}}{\text{cc}}\right) + 0.582 * \text{Yp}\left(\frac{\text{Ibf}}{100\text{ft}^2}\right) \quad \text{(1)}$$

Figure 3 shows the actual versus the predicted mud losses. The R-squared of this model is 0.719; however, the adjusted R-squared is 0.709, which is a modified version of R-squared that accounts for the number of independent variables and should be used for the multi-liner regression (Montgomery, 2001).

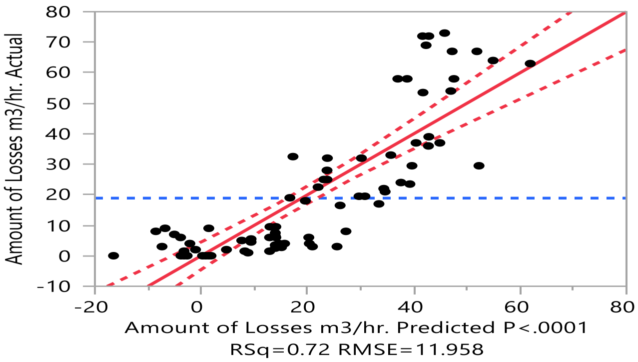

Figure 3. The Actual Versus the Predicted Mud Losses

Figure 4 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 (Montgomery, 2001). The points in the residual plot are randomly distributed, this confirms that a linear regression model is appropriate for the data.

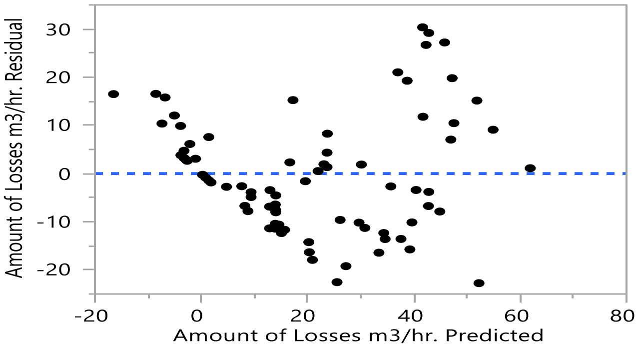

Figure 4. Residual Plot for the Amount of Losses Model

Variance Inflation Factor (VIF) test is used to test for the multicollinearity phenomena in the volume 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 2 shows the summary of the p-values and VIF test. No VIF value exceeded 5, this can lead to the conclusion of no multicollinearity is observed in the model.

Table 2. Summary of P-values and VIF Test

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF Test
Intercept	-1915.757	165.7669	-11.56	<.0001	.
MW, gm/cc	530.7823	194.3577	2.73	0.0077	1.81323
ECD, gm/cc	1144.376	141.6391	8.08	<.0001	1.95161
Yp, Ibf/100ft^2	0.582197	0.27322	2.13	0.0361	1.26712

Figure 5 shows the results of the sensitivity analysis that is conducted for the amount of mud losses model. 10% sensitivity was used in this model, the base parameters are as the following; MW=1.13 (gm/cc), ECD=1.15 (gm/cc), and Yp=13 (Ibf/100ft^2). Figure 5 shows the impact of each parameter on the amount of mud losses model. ECD is the most effective parameter in the amount of mud losses then MW comes after. Also, the amount of mud losses is least influenced by the Yp as shown in Figure 5.

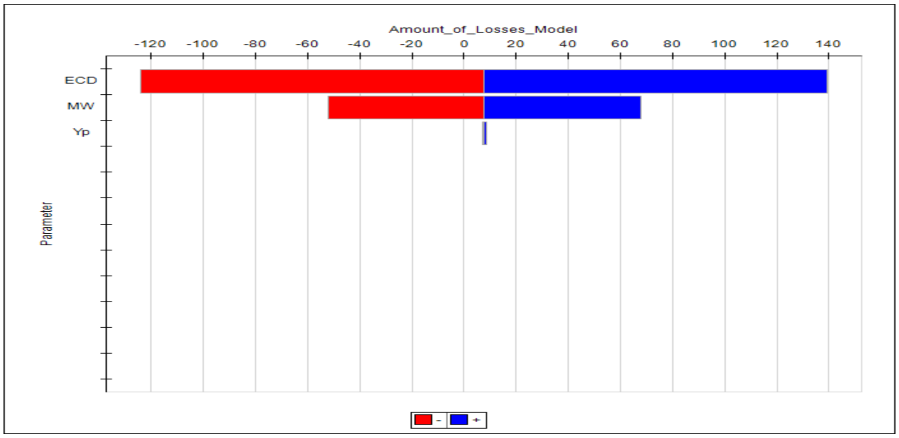

Figure 5. Sensitivity Analysis for the Amount of Mud Losses Model

3.2. EQUIVALENT CIRCULATION DENSITY (ECD) MODEL

Using the same approach in the amount of the loss model, a model for the ECD model has been developed by using a multi-linear regression analysis. 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). 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 Eq. (2):

$$\mathrm{ECD} = 0.9895 + 0.125 * \mathrm{MW}\left(\frac{\mathrm{gm}}{\mathrm{cc}}\right) + 0.0068 * \mathrm{ROP}\left(\frac{\mathrm{m}}{\mathrm{hr}}\right) - 0.000009901 * \mathrm{Q}\left(\frac{\mathrm{L}}{\mathrm{min}}\right) \quad (2)$$

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 Hartha formation. More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017).

3.3. RATE OF PENETRATION (ROP) MODEL

This 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. Other drilling parameters, including ECD, MW and Yp were tested for their significance and found to have a minor impact on the ROP relationship. 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 Hartha formation can be estimated using RPM, SPM, and WOB. The ROP model can be expressed using Equation 3 as the follows:

$$\mathrm{ROP} = -1.312 + 0.007 * \mathrm{SPM} + 0.0124 * \mathrm{RPM} + 0.489 * \mathrm{WOB\ (Ton)} \ldots\ldots\ldots\ldots \text{(3)}$$

Equation 3 provides a good estimate for the ROP in the Hartha formation. In addition, results of Equation 3 provide input for Equation 2 (ECD model). More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017).

4. 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 Hartha formation. The three models developed in the research can be combined to achieve this aim. Mud volume losses can be predicted for the Hartha 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 estimation from Equation 1 can be used to limit overall losses to some value. 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 Hartha formation.

It is important to validate the models prior to field use. Hence, additional the Hartha mud loss events data was collected to test each model, predicted value (the mud loss, ECD, ROP) against the actual, new data. Table 3 is only example to summarize the number of mud loss events in new wells mud loss events compared to the original events used in the model development for FCL mud. Figures 6-8 are only examples of predicted values of ROP, ECD and the volume loss plotted against actual data, respectively, and all three figures are for severe and complete losses. There is a strong correlation between predicted and actual for all ROP, ECD, and losses models results.

Table 3. Summary of the Application of the Real Field Data (FCL Drilling Mud)

Type of the Losses	**New Wells**	**Original Wells**	**Total New Wells**	**Total Old Wells**	**Total Wells**
Partial Losses	22	6	60	17	77
Severe Losses	38	11			

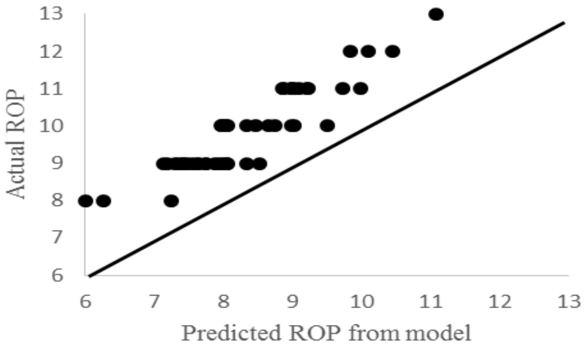

Figure 6. Actual vs. Predicted ROP for Severe and Complete Losses (FCL Mud)

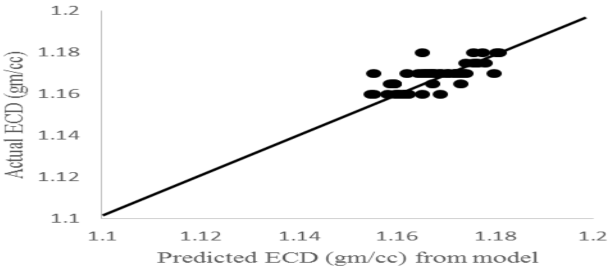

Figure 7. Actual vs. Predicted ECD for Severe and Complete Losses (FCL Mud)

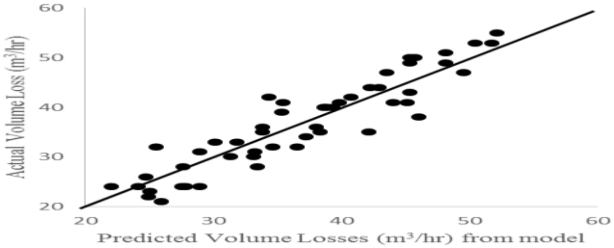

Figure 8. Actual vs. Predicted Volume Loss for Severe and Complete Losses

5. COMPARISON OF FORMATION SPECIFIC MODELS

The methodology applied to the models developed for the Hartha formation have also been applied to two other limestone formations, the Dammam and Shuaiba , which also pose great risk for lost circulation during drilling operations. Table 4 shows the average MW and depth for each formation as well as the first, second, and third coefficients (C1, C2, and C3) for the formation's corresponding volume loss model.

Table 4. Summary of Models Coefficients

Formation	MW	Depth	C1	C2	C3
Dammam	1.055	550	1019.371	808.816	0.557
Hartha	1.125	1755	530.782	1144.376	0.582
Shuaiba	1.155	3040	760	908	4

Figures 9-11 show C1, C2, and C3 for each formation plotted as a function of depth. Figures 12-14 show C1, C2, and C3 values for each formation plotted as a function of MW. A simple linear trend has been included for all figures. These plots show commonality between coefficient variation as a function of depth and MW. This commonality, combined with general trends of the individual coefficients suggest the possibility of estimation of the coefficients determined through this methodology without the use of such an extensive data set.

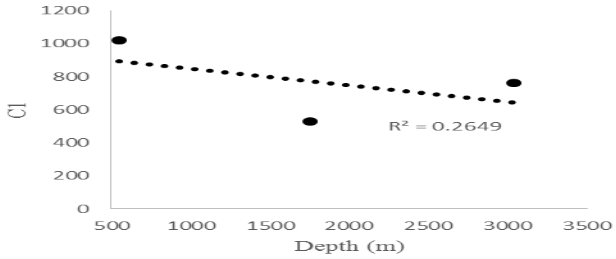

Figure 9. Coefficient 1 versus Depth

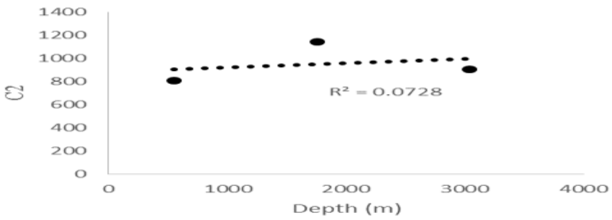

Figure 10. Coefficient 2 versus Depth

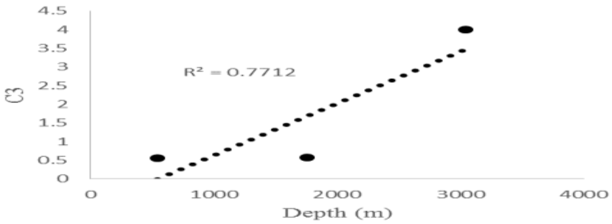

Figure 11. Coefficient 3 versus Depth

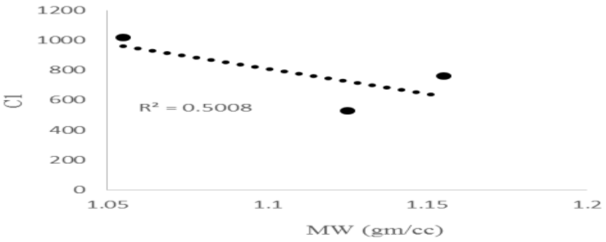

Figure 12. Coefficient 1 versus MW

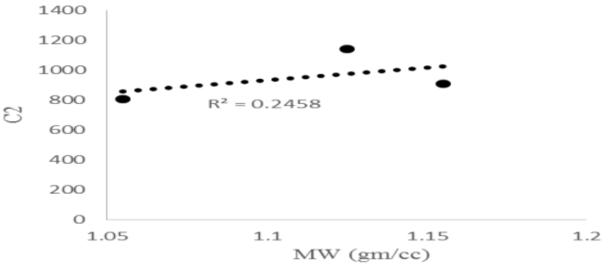

Figure 13. Coefficient 2 versus MW

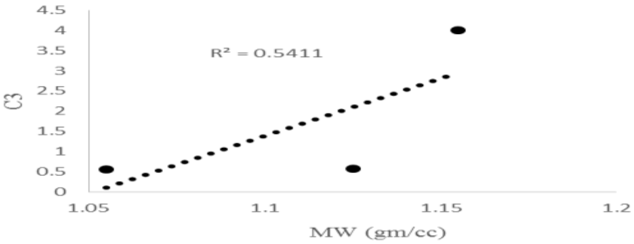

Figure 14. Coefficient 3 versus MW

6. RECOMMENDED KEY DRILLING PARAMETERS TO DRILL THE HARTHA FORMATION (PREVENTIVE APPROACHES)

Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al., 2005). All those remedies/techniques that are applied prior to entering lost circulation zones to prevent the occurrence of losses can be defined as proactive methods. The main advantage of using these techniques are to increase the chances of avoiding or minimizing lost circulation in the Hartha formation. Many methods are used to mitigate mud loss prior to entering the lost circulation zone. Some examples of these methods are waiting method, reduction of pump rate, reduction of mud weight, increase drilling fluid viscosity, and using bit without nozzles. On this study, the ranges of key drilling parameters to drill the Shuaiba formation are identified and summarized by reviewing historical data, integrated analysis, and comprehensive statistical study. As a proactive approach, each key drilling parameter is analyzed separately to estimate the best operational range that will prevent or mitigate mud losses Figures 15 is only example of estimated the best range of mud weight parameter.

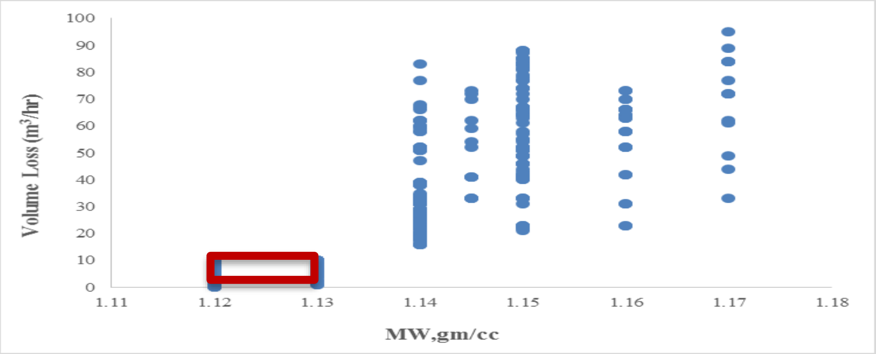

Figure 15. Mud Weight versus Volume Loss (more than 300 Wells)

Hence, after doing the analysis for various drilled wells in Rumaila field (The Hartha Formation), it is recommended to use the following values of drilling mud properties and operational drilling parameters to avoid or mitigate lost circulation issue during drilling operations. Table 5 shows recommended parameters to drill the Hartha formation. In some cases, under the same recommended parameters, the Hartha formation will suffer from severe losses circulation problem or even complete losses. In these cases, the major reason to have these types of the mud losses is initially using a high range of the drilling properties and operational drilling parameters. In different words, the lost circulation will be initiated due to high ranges of below parameters. After problem occurred even if low ranges of these parameters are used, the problem will continue, and we need to do the corrective approaches to mitigate or stop mud losses.

Table 5. Recommended Drilling Mud Properties and Operational Drilling Parameters for the Hartha Formation

Property	**Minimum Value**	**Maximum Value**
Mud Weight (MW, gm/cc),	1.12	1.13
Equivalent Circulation Density (ECD), (gm/cc)	1.13	1.15
Yield Point (Yp), (Ibf/100ft^2) (Polymer Mud)	20	24
Yield Point (Yp), (Ibf/100ft^2) (FWB Mud)	13	15
Plastic Viscosity (PV), cp	9	14
Weight of Bit (WOB), Ton	7	13
Strokes per Minute (SPM)	100	120
Flow Rate (Q), L/min	1760	2112
Revolutions per Minute (RPM)	60	70
Rate of Penetration (ROP, m/hr.)	5	9
Bit Nozzles	Without Nozzles	Without Nozzles

7. RECOMMENDED LOST CIRCULATION STRATEGY TO THE HARTHA FORMATION (CORRECTIVE METHODS)

In case the preventive measures didn’t work, remedial treatments should be used to stop the mud losses. Hence, it is recognized that there is no single solution to lost circulation, and that most treatment and trial-and-error. However, the screening guide presents a high-level ‘go to’ document with coherent guidelines, which engineers can utilize in making decisions regarding lost circulation treatments in the Hartha formation. The part also employed a thorough literature review to identify relevant information that could be included in developing the screening guide.

This section will summarize the required treatments for each type of the lost circulation. More than 300 wells have been analyzed to figure out the successful remedies for each type of the losses, and these treatments are classified by relying on the mud losses classifications to get effective remedies, minimize cost, reduce non-productive time, and avoid unwanted consequences due to inappropriate actions. A lost circulation screening criterion is presented for this formation based on the historical mud loss and lost circulation problems, materials used to mitigate the problems, and potential solutions found by this study. In addition, practical field information from a range of sources were reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the Hartha formation (Al-Hameedi et al, 2017). The economic evaluation is conducted for partial, severe, and complete losses. Table 6 is only example to show the results of the economic evaluation for complete losses treatments with their probabilities. Figure 16 provides guidance for drilling through the Hartha formation and handling loss circulation through this formation.

Table 6. Complete Losses Economic Calculations and Probabilities

Treatment Name	**Required Addition, kg/m3**	**Cost, \$/m^3**	**Waiting Period, (hrs)**	**NPT Cost, \$/1hr**	**Total Cost, (\$)**	**Success%**	**Fail%**
Cement Plug	1102.5	351	18	1500	27351	47	53
H.V Mud +Cement Plug	Bentonite (100), Cement (1029)	382.30	20	1500	30382.30	64	36
DOB Plug	Formula for 1 m^3 Oil base 0.70 m^3 Bentonite 800 kg	603.6	10	1500	15603.6	80	20
DOBC Plug	Formula for 1 m^3 Oil base 0.72 m^3 Bentonite 450 kg Cement 450 kg	645.75	12	1500	18645.75	78	22

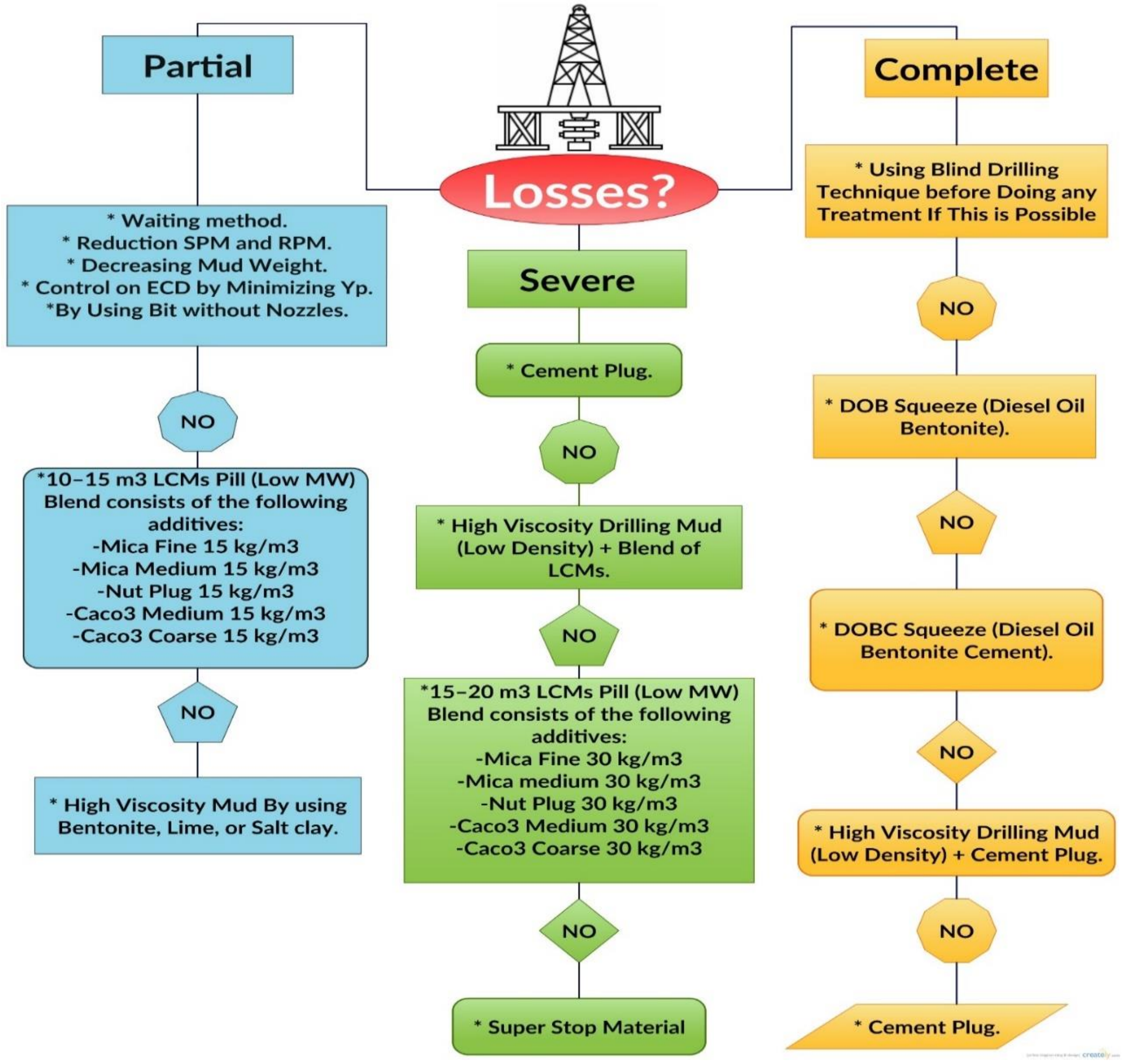

Figure 16. Treatment Strategy to the Hartha Formation

8. GENERALIZATION OF THE VOLUME LOSS MODEL FOR THE HARTHA FORMATION

The above three statistical models have been generalized to come up with one equation for Hartha formation (only volume loss equation) to predict the mud losses anywhere in Basra's oil fields. ROP model (Equation 3) has been substituted in ECD model (Equation 2), and then ECD model has been substituted in volume loss model (Equation 1), Figure 17 illustrates the implemented procedures for the generalization of volume loss model.

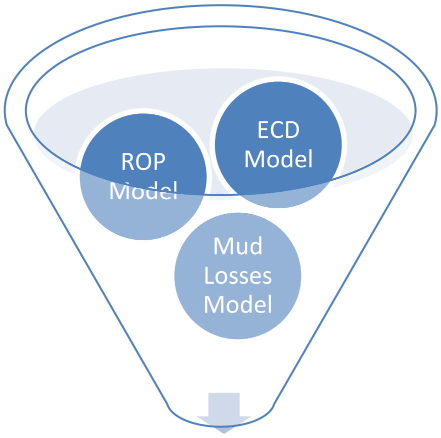

Figure 17. Generalization of Volume Loss Model for the Hartha Formation

Based on MW, Q, RPM, WOB, and Yp a model to estimate the volume loss was developed to estimate the loss volume before drilling the Hartha formation in Basra's oil fields. The volume loss model developed is expressed by Eq. (4):

$$\text{Mud Losses} = -793.607 + 673.829 * MW - 0.008235 * Q + 0.096125 * RPM + 3.80505 * WOB + 0.582 * Yp \quad (4)$$

9. CONCLUSION

This paper has provided a detailed study of lost circulation, including a brief review of fundamentals of lost circulation, analyzing real field data, discussion of methods of mitigating losses, and an introduction to newer methods of loss control used in industry. Lost circulation presents a lot of challenges while drilling operations. To address these problems, a number of methods/techniques have evolved over the years. Lost circulation solutions may be applied before or after the occurrence of the problem. The solutions are therefore grouped into preventive and remedial respectively.

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

Based on this study, the following conclusion are made:

1. One challenge in drilling wells in the Rumaila field is the inconsistency of approaches to the mud losses problem. Hence, a formalized methodology for responding to losses in the Rumaila field is developed and provided as means of assisting drilling personnel to work through the mud losses problem in a systematic way.
2. The volume loss model, which was developed, is capable of predicting lost circulation events and volumes in the Hartha formation.
3. ECD, MW, and Yp have a much greater effect on the volume of mud losses than SPM, RPM, and ROP.

4. The ECD model was developed to estimate ECD within the Hartha formation without knowledge of all operational drilling parameters. This model can then be used to estimate the ECD, which is required as in input to the volume loss model.
5. The ROP developed here may be used to estimate the ROP within the Hartha formation without knowledge of all operational drilling parameters. This model is required to estimate the ROP prior to drilling, to be used and in input to the ECD and subsequent volume loss model.
6. The parameters impacting volume loss, ECD, and ROP were examined to determine those which impact each the greatest. Those parameters were the basis for each model, and the Variance Inflation Factor (VIF) test was used to test for the multicollinearity phenomena in each model to maximize the accuracy, and improve each mathematical model.
7. Comparison of three volume loss, ECD, and ROP models shows strong trends for the coefficients in these models with respect to depth. This suggests the possibility of combining field data and models from multiple formations to develop a non-formation specific model for volume losses.
8. The optimal parameters summarized are all within the range of parameters currently used to drill wells for thief zone in Rumaila field, and it should be feasible to restrict the properties to these values and still successfully drill through the Hartha zone.
9. Lost circulation problem in the Hartha formation should be prevented in the first place rather than controlling it; therefore, a keen observation and a backup strategy should be employed in the field to mitigate this problem.

10. Treatments for partial, severe, and complete losses for the Hartha formation are summarized in a flow chart. This flow chart should be used to treat the mud losses in the Hartha formation depending on the type of the mud losses.
11. The highest probability of success treatment should be used to treat the mud losses even if it is not the cheapest to avoid the repetition of treatments which reduces the NPT. Using a low-probability of success treatment may not be effective and the usage of multiple treatments may be required, even if it is cheaper than other treatment, but the NPT will be higher which increases the cost.
12. NPT is the most influence factor in the cost of the mud losses treatments. Thus, any treatment that has a low probability of success should not be used as a first choice to treat mud losses.

NOMENCLATURE

Symbol	**Description**
D	Depth
DDR	Daily Drilling Report
DOH	Diameter of Open Hole
ECD	Equivalent Circulation Density
FP	Fracture Pressure
Ft/min	foot per minute
FWB	Fresh Water Bentonite
gm/cc	gram per cubed centimeter
HP	Hydrostatic Pressure
H. V	High Viscosity
Ib/bbl	pounds per barrel
Ib/ft^3	pounds per cubed feet
in	Inch
Kg/m^3	Kilogram per cubed meter
LCMs	Lost Circulation Materials
L/min	Litter per minute
m	meter
m^3/hr	cubed meter per hour
MW	Mud Weight
NPT	Non-productive Time

O.E.D.P	Open End Drill Pressure
ppg	pounds per gallon
PP	Pore Pressure
Q	Flow Rate
ROP	Rate of Penetration
RPM	Revolutions per Minute
SPM	Stroke per Minute
TFA	Total Flow Area
WOB	Weight of Bit
WOC	Waiting of Cement
WON	Without Nozzles
Yp	Yield Point Viscosity
$	Dollar

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IV. A NEW APPROACH TO REDUCE LOST CIRCULATION NON-PRODUCTIVE TIME

ABSTRACT

Fluid losses during drilling lead to greater expenses from mud loss, difficulty in well control and zonal isolation, and non-productive time (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 Rumalia field in Iraq, in which these events are common. Mud loss data from more than 300 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 volume loss 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 was 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.

Proactive approaches are made prior to entering the Shuaiba formation to prevent or reduce the occurrence of the lost circulation. Key drilling parameters are estimated to be

used during drilling through this formation. In case preventive measures didn’t work, corrective actions are determined for each type of the mud losses to provide effective remedies, minimize non-productive time, and reduce cost. Moreover, the best-lost circulation strategy to the Shuaiba formation is concluded and summarized depending on a comprehensive statistical work, the most prevalent industry practices, technical papers, textbooks, and economic analysis evaluation to determine the most successful remedies for each type of the losses. These treatments are classified by relying on the mud losses classifications to avoid unwanted consequences due to inappropriate actions. In addition, 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 limit operational parameters to mitigate such losses in future wells in fields with similar lithology.

1. INTRODUCTION

Drilling mud accounts for a major expense in drilling oil and gas wells. The drilling mud is circulated through the drill string and drill bit, to remove cuttings from the borehole and to enable drill bit performance. Drilling mud is specifically formulated to develop a thin coating on the borehole wall, referred to as a ‘mud cake’ which limits fluid losses to the formations already drilled and exposed in the borehole, as drill bit proceeds deeper and deeper.

The materials of the drilling fluid are so expensive, companies spent $7.2 billion in 2011 and it is expected to reach $12.31 billion in 2018 as the global market for drilling fluid indicates, which shows a vigorous yearly maximize by 10.13% (Transparency Market Research, 2013). The cost of the drilling mud is equivalent to averages 10% of total well costs; however, drilling-fluid can extremely impact the ultimate expenditure (Darley and Gray, 1988). Lost circulation events, defined as the loss of drilling fluids into the formation, are known to be one of the most challenging problems to be prevented or mitigated during the drilling phase. The severity of the consequences varies depending on the loss severity; it could start as just losing the drilling fluid and it could end in a blowout (Messenger, 1981). Among the top ten drilling challenges facing the oil and gas industry today is the problem of lost circulation. Major progress has been made to understand this problem and how to combat it. However, most of the products and guidelines available for combating lost circulation are often biased towards advertisement for a service company.

Lost circulation is a common drilling problem especially in highly permeable formations, depleted reservoirs, and fractured or cavernous formations (Nayberg and Petty, 1986). The range of lost circulation problems begins in the shallow, unconsolidated formations and extends into the well-consolidated formations that are fractured by the hydrostatic head imposed by the drilling mud (Moore, 1986). By industry estimates, more than 2 billion USD is spent to combat and mitigate this problem each year (Arshad et al., 2015). Two conditions are both necessary for lost circulation to occur downhole: 1) the pressure in the wellbore must exceed the pore pressure and 2) there must be a flow pathway for the losses to occur (Osisanya, 3002). Subsurface pathways that cause, or lead to, lost circulation can be broadly classified as follows:

1. Induced or created fractures (fast tripping or underground blow-outs).
2. Cavernous formations (crevices and channels).
3. Unconsolidated or highly permeable formations.
4. Natural fractures present in the rock formations (including non-sealing faults).

The rate of losses is indicative of the lost pathways and can also give the treatment method to be used to combat the losses. The severity of lost circulation can be grouped into the following categories (Basra Oil Company, 2012):

1. Seepage losses: up to 1 m^3/hr lost while circulating.
2. Partial losses: 1 – 10 m^3/hr lost while circulating.
3. Severe losses: more than 15 m^3/hr lost while circulating.
4. Total losses: no fluid comes out of the annulus.

There are multiple reasons that may initiate lost circulation in the Shuaiba formation. Table 1 illustrates the major factors that have an impact on lost circulation issue. Table 2 summarizes the unwanted consequences due to mud losses in this formation, and its associated detrimental effects such as loss of rig time, stuck pipe, blow-outs, and less frequently, the abandonment of expensive wells (Al-Hameedi, et al., 2017a).

Table 1. Factors Impact Lost Circulation

Property	The Impact on Lost Circulation
Lithology	Limestone is the lithology for the Shuaiba formation. Limestone has natural fractures which cause lost circulation mud, and these vugs, slots, and channels absorb the drilling fluids. In addition, Limestone will be weak and prone to induced fracture which causes mud loss.
MW	Mud pressure is one of the most important factors which can lead to induce or aggravate losses. Sometimes, the excess mud weight only results in partial losses in these formations, but more frequently there are severe or complete losses. Therefore, it is very important to design a mud weight that limits losses, and it is prudent to precisely monitor drilling mud density during drilling this formation to avoid mitigate lost circulation mud.
ECD	This property is related with real downhole pressure (friction pressure) in the annulus. Therefore, it is recommended to monitor this parameter during drilling operations. This property has a linear relationship with yield point, mud weight, flow rate, and rate of penetration.
Yp	This parameter is a major cause of mud loss. By increasing yield point (Yp) of 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 pressure loss in the annulus. Therefore, it is crucial to control yield point within allowed limits.
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 shutdown. Therefore, the gel strength of the mud indirectly affects mud losses.
PV	This parameter is related to effective drilling density. It is considered to be the second component of the drilling fluid viscosity. In addition, this property is represented by the friction forces between molecules of the drilling mud. This parameter has directly or indirectly role on lost circulation issue. In other words, by increasing plastic viscosity, the ECD will be increased. Thus, it is recommended to use a proper range of this parameter.
SPM & Q	Both parameters are related to mud pump pressure. They are responsible for drilling mud cycle from mud system to wellbore by using mud pumps. In addition, these properties are associated with effective wellbore cleaning into the annulus. Both of them have either directly or indirectly role in lost circulation issue. In other words, by using high mud pump pressure, extra annulus pressure will be exerted on the thief zone. Hence, it is recommended to use a proper range of these parameters.
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.
WOB	It has a significant impact on the rate of penetration. By increasing weight of bit, the rate of penetration (ROP) will be maximized; therefore, effective mud weight will be increased. Hence, the weight on bit has directly or indirectly influence mud loss. Thus, it is practically interesting to use a good range of this parameter to avoid unwanted consequences.
ROP	Excessive cutting and high ROP will lead to increase downhole pressure. In addition, ROP and mud weight have a linear relationship with ECD. ROP has a linear relationship with WOB, SPM, and RPM. Therefore, it is prudent to use appropriate ranges of this property to avoid increasing annular pressure losses (APL) and equivalent circulation density (ECD).
Jet Forces	Higher jet velocity because of bit nozzles selection lead to 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.

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 a 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 leads to mechanical stuck pipe due to lost circulation.

2. METHODOLOGY

The simple linear regression predicts the response of Y based on one predictor X. Mathematically, the simple linear regression is represented as the following:

$Y \approx \beta_0 + \beta_1 X$ ………………………………………………………………………….. (1)

Where β_0 represents Y intercept and $\beta_1$represents the coefficient of X . The symbol $\approx$ “approximately equal to” is written to show this is an estimation (regression) for the real value (James et al., 2013).

Since mud loss is affected by multiple parameters, it is crucial to use a multiple linear regression instead of the simple linear regression. Unlike the simple linear regression, the multiple linear regression gives each predictor X a separate slope term (coefficient). Let’s assume there is n number of predictors X, the general formula of the multiple linear regression will be as the following:

$\mathrm{Y} = \beta_0 + \beta_1 \mathrm{X}_1 + \beta_2 \mathrm{X}_2 + \cdots + \beta_n \mathrm{X}_n$ ………………………………………………… (2)

Whereβ_1, β_2, and β_n represent different slope terms for each predictor. The βs are unknown parameters need to be estimated. If the number of predictors (n) =1, then it is a simple linear regression problem and it is modeled in 2D. When n=2, the mean functions is a plane in 3D as shown in Figure 1 When n > 2, the mean function is a hyperplane. The generalization of the n-dimensional plane is (n+1)-dimensional space (Weisberg, 3005).

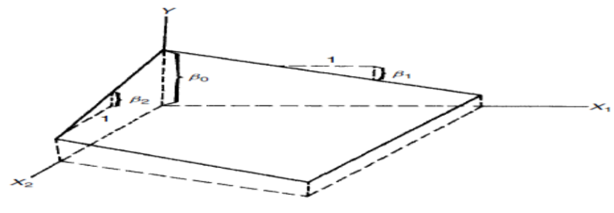

Figure 1. Linear Regression Plane with n=2 Predictors (Weisberg, 3005)

There are many methods used to estimate theβs. However, the most common method is called the least square method (James et al., 2013). The criterion function that is used on this method is based on the residuals, which represent the distance between the y-values and the fitted line as shown in Figure 2 (Weisberg, 3005).

The least square method estimates the βs that minimize the following function (James et al., 2013; Weisberg, 3005):

$$RSS = \sum_{i=1}^{n}(y_i - \hat{\beta}_0 - \hat{\beta}_1 x_{i1} - \hat{\beta}_2 x_{i2} - \cdots - \hat{\beta}_n x_{in})^2 \text{ ....(3)}$$

Where RSS is the residual sum of the squares. The detailed algorithm for finding the βs for multiple linear regression is very complicated and represented using matrix algebra (Weisberg, 3005). Thus, it is beyond the scope of this paper.

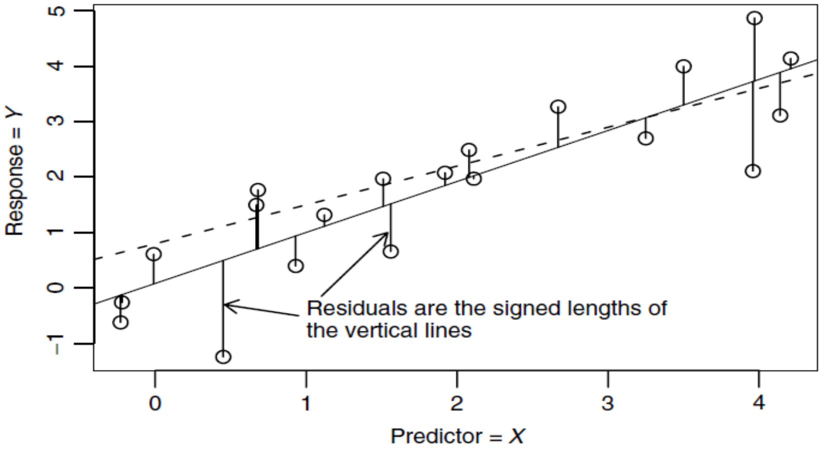

Figure 2. Example of the Residuals in Simple Linear Regression (Weisberg, 3005)

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 300 wells drilled in the Rumaila field were identified through reading and summarizing daily drilling reports (DDR), final well reports, and technical report. Critical drilling parameters such as mud weight (MW), equivalent circulation density (ECD), yield point (Yp), rate of penetration (ROP), strokes per minute (SPM), flow rate (Q), revolution per minute (RPM), plastic viscosity (Pv), 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 only example well data used in the study.

Table 3. Well 1 Data Events, the Shuaiba Formation

Depth (m)	**MW (gm/cc)**	**YP (Ibf/100ft^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 2 Data Events, the Shuaiba Formation

Depth (m)	**MW, (gm/cc)**	**YP (Ibf/100ft^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

The multiple linear regression analysis was used for modeling because there are multiple drilling parameters, some of which are inter-related. Multiple linear regression models can have multiple independent variables for one dependent variable (Weisberg, 3005). It was necessary to first identify which drilling parameters had the greatest impact on the amount of mud losses. Multiple linear 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. After finishing building the models, new data were obtained (data not included in building the models) to test the efficiency of the models with the new data.

Also, 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 (Al-Hameedi, et al., 2017a).

Recommended key drilling parameters have been determined in this paper to prevent or mitigate lost circulation in the Shuaiba formation. This is done based on reviewing data of key drilling parameters. In addition, mud losses treatments events are examined, and statistical analysis is conducted for these remedies. The probability of each treatment is calculated by adding the number of times they were used successfully divided by the total number of attempts. An economic evaluation is performed for the same data based on the cost of each material and the NPT, the rig cost is estimated to be 36000 ($/day). Table 5 shows the prices for lost circulation materials that are used in the economic evaluation (Halliburton, 2016). Thus, the lost circulation strategy has been developed by depending on statistical work and economic analysis to efficiently remedy in terms of stopping mud losses, minimizing non-productive time, and reducing cost. This treatment strategy has been classified by relying on the type of mud loss. Practical field information from a range of sources was reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the Shuaiba formation (Al-Hameedi, et al., 2017b).

Table 5. Cost of Lost Circulation Materials (Halliburton, 2016)

Material Name	**Price for each ($/Ton)**	**Price for each ($/kg)**
Bentonite	317	0.317
Mica Fine	500	0.5
Mica Medium	700	0.7
Nut Plug	960	0.96
$CaCO_3$ Medium	313	0.313
$CaCO_3$ Coarse	350	0.35
Super Stop Material	1300	1.2
Blend of LCM	900	0.9
Cement	318	0.318
Diesel Oil	500	0.5

3. STATISTICAL MODELS

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 300 wells drilled in the 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 Shuaiba 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 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.

3.1. VOLUME LOSS MODEL

First, it is necessary to identify which drilling parameters had the greatest impact on mud volume loss, a multiple 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 (Schlotzhauer, 3007). 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 3 to 5 show the leverage plots for MW, ECD, and Yp respectively.

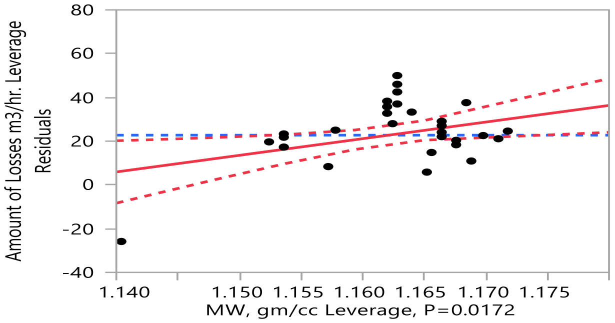

Figure 3. Leverage Plot of MW for the Amount of Losses Model

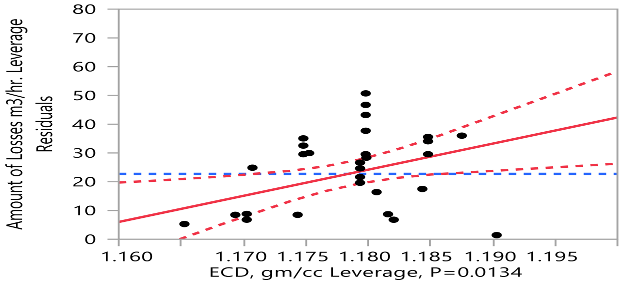

Figure 4. Leverage Plot of ECD for the Amount of Losses Model

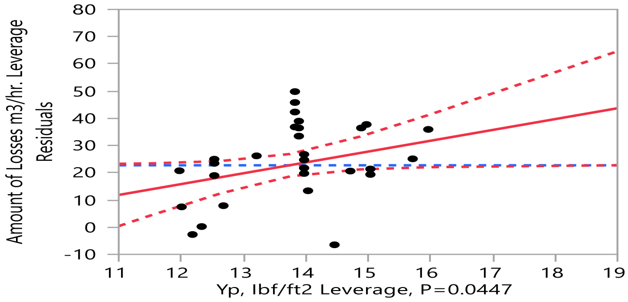

Figure 5. Leverage Plot of Yp for the Amount of Losses Model

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 4:

$$\text{Losses} = -1985 + 760 * \text{MW}\left(\frac{\text{gm}}{\text{cc}}\right) + 908 * \text{ECD}\left(\frac{\text{gm}}{\text{cc}}\right) + 4 * \text{Yp}\left(\frac{\text{Ibf}}{100\text{ft}^2}\right) \text{ .... } (4)$$

Figure 6 shows the actual versus the predicted mud losses. The R-squared of this model is 0.83; 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 multiple linear regression (Montgomery, 3001). Since there are multiple independent variables, the adjusted R-squared should be used instead of the R-squared.

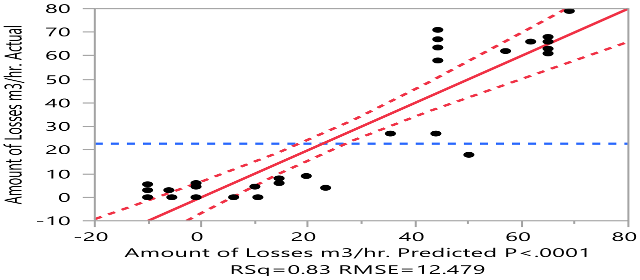

Figure 6. The Actual Versus the Predicted Mud Losses

Figure 7 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 (Montgomery, 3001). The points in the residual plot are randomly distributed. This confirms that a linear regression model is appropriate for the data.

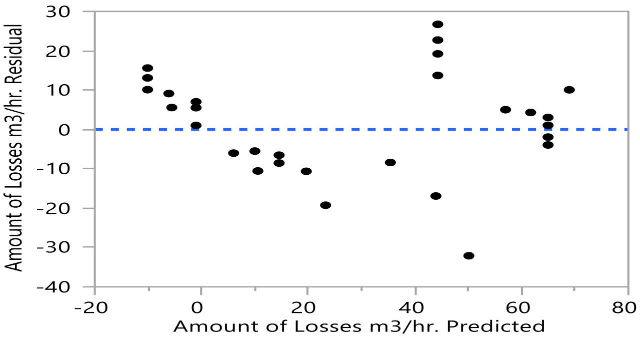

Figure 7. Residual Plot for the Amount of Losses Model

Collinearity (also known as multicollinearity) refers to the condition where two or more independent variables in a multiple linear regression model are highly correlated (Yan and Su, 3009). 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 (Ott et al., 2016). One of the most common methods used to detect collinearity is variance inflation factor (VIF). The VIF method was used to test for the multicollinearity in the amount of the loss model. Montgomery (3001) suggested that if VIF is greater than 5 or 10, then the regression coefficients are poorly estimated due to multicollinearity. Table 6 shows the summary of the p-values and VIF test. No VIF value exceeded. Hence, no multicollinearity is observed in the model.

Table 6. Summary of P-values and VIF Tests

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF Test
Intercept	-1985.391	267.7215	-7.42	<.0001	.
ECD, gm/cc	908.0416	348.211	2.61	0.0134	4.86761
Yp, Ibf/ft^2	3.981626	1.909781	2.08	0.0447	2.09641
MW, gm/cc	760.1526	303.5788	2.50	0.0172	3.27012

Figure 8 presents a tornado chart of results of the sensitivity analysis for the three significant parameters (ECD, MW, and Yp). 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 (Ibf/100ft2). Figure 8 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 8, but Yp is a significant parameter and therefore included in the model.

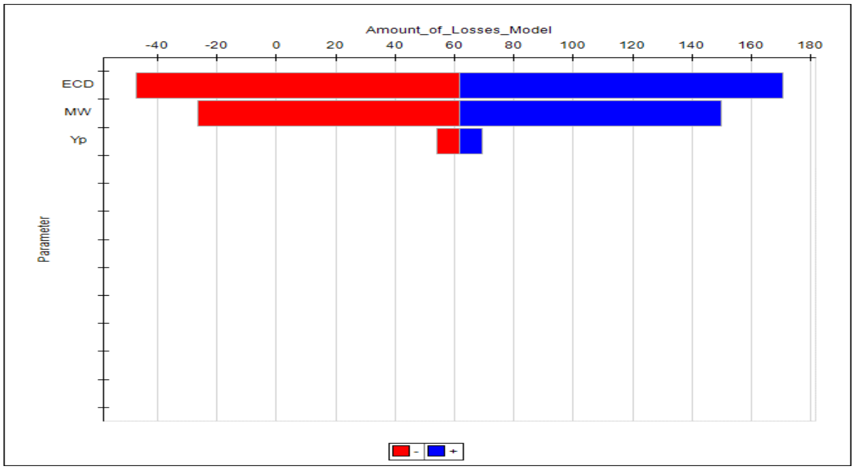

Figure 8. Sensitivity Analysis of the Amount of Mud Losses Model

3.2. EQUIVALENT CIRCULATION DENSITY (ECD) MODEL

Using the same approach in the amount of the loss model, a model for the ECD model has been developed by using a multiple linear regression analysis. 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). 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 multiple linear 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 5:

$$\mathrm{ECD} = 0.977 + 0.164 * \mathrm{MW}\left(\frac{\mathrm{gm}}{\mathrm{cc}}\right) + 0.00664 * \mathrm{ROP}\left(\frac{\mathrm{m}}{\mathrm{hr}}\right) - 0.00000646 * \mathrm{Q}\left(\frac{\mathrm{L}}{\mathrm{min}}\right) \quad \ldots\ldots\ldots\ldots \quad (5)$$

ECD calculated using Equation 5 can be used as an input for Equation 4 (the amount of the mud losses model). ECD is a parameter that can be found during the drilling operation only. Equation 5 provides a good estimation for ECD in the Shuaiba formation. More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017a).

3.3. RATE OF PENETRATION (ROP) MODEL

Once again, using the same statistical analysis, the ROP model has been developed. This model developed focused on identifying parameters which affected ROP since ROP was found to be a significant factor of the ECD model (Equation 5). Several drilling parameters were tested to determine their significance. After performing the multiple linear regression analysis, three parameters, including RPM, SPM, and WOB were found to be significant. Other drilling parameters, including ECD, MW and Yp were tested for their significance and found to have a minor impact on the ROP relationship. 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 multiple linear 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 6 as the following:

$$\mathrm{ROP} = -5.556 + 0.01362 * \mathrm{SPM} + 0.01669 * \mathrm{RPM} + 0.578 * \mathrm{WOB}\ (\mathrm{Ton}) \quad \ldots\ldots.(6)$$

Equation 6 provides a good estimate for the ROP in the Shuaiba formation. In addition, results of Equation 6 provide input for Equation 5 (ECD model). More details on the advantages of models construction and utilization are provided in the literature (Al-Hameedi, et. al, 2017a).

4. 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 6. The resulting value for ROP is then combined with values for MW and Q in Equation 5, to calculate ECD. Finally, the calculated value of ECD can be combined with MW and Yp in Equation 4, to calculate a predicted mud loss. A mud loss plot from Equation 4 can be used to limit overall losses to some value. Then, each of the operating parameters can be determined from Equations 4, 5, and 6.

It is important to validate the models prior to field use. Hence, additional the Shuaiba mud loss events data were collected to test each model, predicted value (the amount of the mud loss, ECD, ROP) against the actual, new data. Table 7 summarizes the number of mud loss events in new well mud loss events compared to the original events used in the model development. Table 6 shows the mud loss event counts for original wells used to develop the models and wells used for testing model results. In addition, Figures 9-11 are plots of predicted values of ROP, ECD and the amount of the mud loss plotted against actual data, respectively, and all three figures are for partial losses. While Figures 12-14 are plots of predicted values of ROP, ECD and the amount of the mud loss plotted against actual data, respectively, and all three figures are for severe and complete losses. There is a strong correlation between predicted and actual for all ROP, ECD, and losses models results.

Table 7. 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			

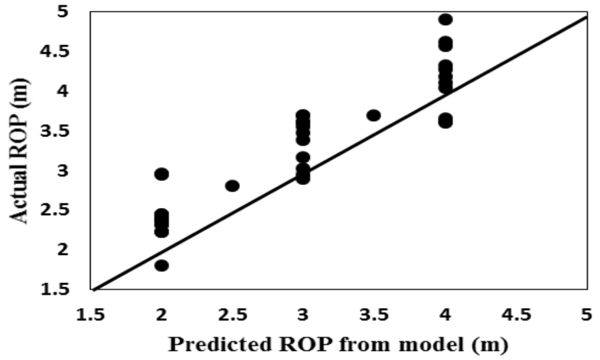

Figure 9. Actual vs. Predicted ROP for Partial Losses

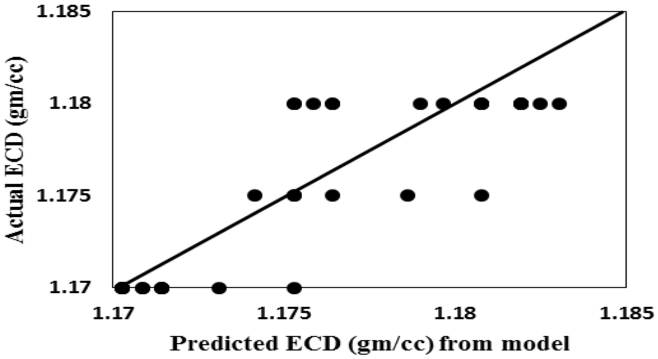

Figure 10. Actual vs. Predicted ECD for Partial Losses

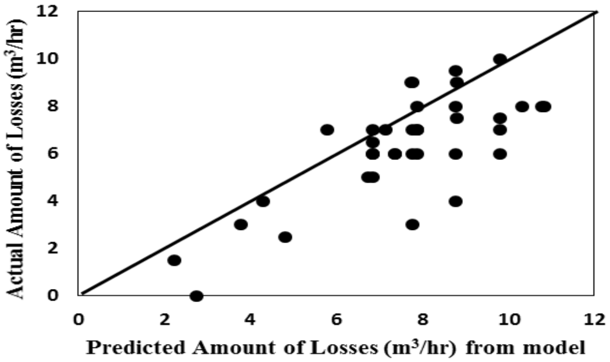

Figure 11. Actual vs. Predicted Amount of Losses for Partial Losses

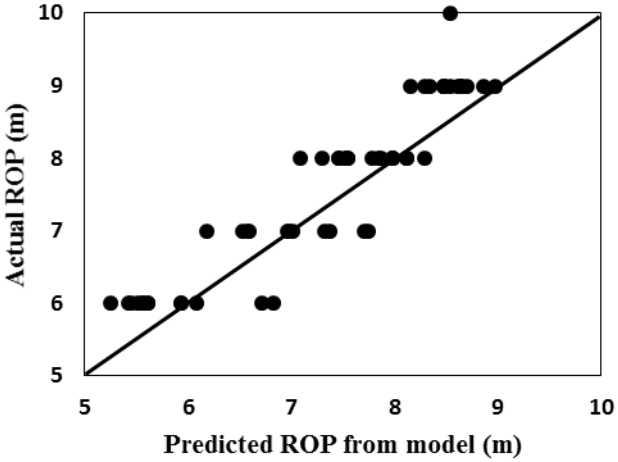

Figure 12. Actual vs. Predicted ROP for Severe and Complete Losses

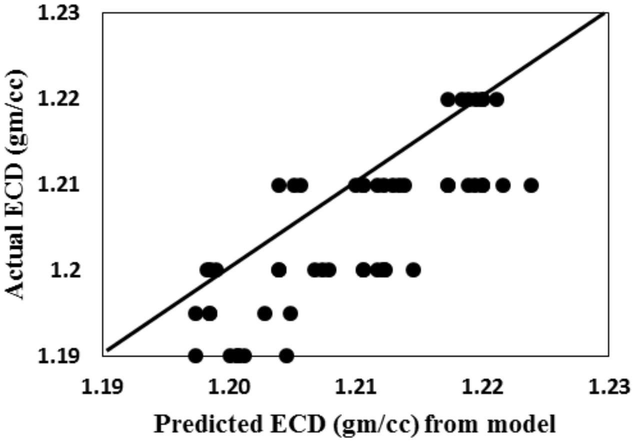

Figure 13. Actual vs. Predicted ECD for Severe and Complete Losses

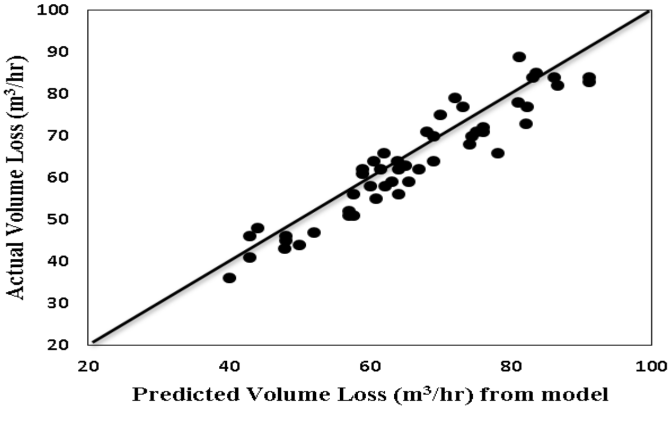

Figure 14. Actual vs. Predicted Amount of Losses for Severe and Complete Losses

5. RECOMMENDED KEY DRILLING PARAMETERS TO DRILL THE SHUAIBA FORMATION (PREVENTIVE APPROACHES)

Conventional lost circulation materials (LCMs), including pills, squeezes, pretreatments and drilling techniques often reach their limit in effectiveness and become unsuccessful when drilling deeper hole sections where some formations are depleted, structurally weak, or naturally fractured and faulted (Wang et al., 3005). Many methods are used to mitigate mud loss prior to entering the lost circulation zone. Some examples of these methods are waiting method, reduction of pump rate, reduction of mud weight, increase drilling fluid viscosity, and using bit without nozzles. On this study, the best ranges of key drilling parameters to drill the Shuaiba formation are identified and summarized by reviewing historical data, integrated analysis, and comprehensive statistical study. As a proactive approach, each key drilling parameter is analyzed separately to estimate the best operational range that will prevent or mitigate mud losses. Figures 15 is an example of how estimating the best range of mud weight parameter.

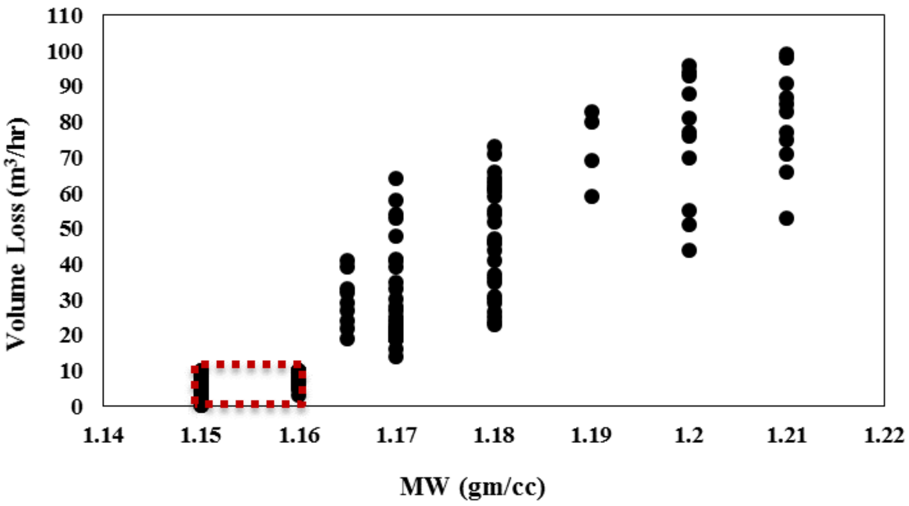

Figure 15. MW versus Volume Loss (more than 300 Wells)

Table 8 shows recommended parameters to drill the Shuaiba formation. In some cases, under the same recommended parameters, the Shuaiba zone will suffer from severe mud loss problem or even complete losses. The major reason is these losses occur due to using a high range of key drilling parameters before using the recommended parameters. If the recommended key drilling parameters are not utilized initially, and the lost circulation problem occurs, the key drilling parameters can't be used afterward and the only option left is to use treatments to mitigate or stop losses.

Table 8. Recommended Key Drilling Parameters for the Shuaiba Formation

Property	**Minimum Value**	**Maximum Value**
Mud Weight (MW, gm/cc),	1.15	1.16
Equivalent Circulation Density (ECD), (gm/cc)	1.16	1.18
Yield Point (Yp), (Ibf/100ft^2)	12	13
Plastic Viscosity (PV), cp	12	15
Weight of Bit (WOB), Ton	10	14
Strokes per Minute (SPM)	80	90
Flow Rate (Q), L/STK	1408	1584
Revolutions per Minute (RPM)	55	65
Rate of Penetration (ROP, m/hr.)	2	4
Bit Nozzles	Without Nozzles	Without Nozzles

6. RECOMMENDED LOST CIRCULATION STRATEGY TO THE SHUAIBA FORMATION (CORRECTIVE METHODS)

In case the preventive measures didn’t work, remedial treatments should be used to stop the mud losses. Hence, it is recognized that there is no single solution to lost circulation and that most treatment and trial-and-error. However, the screening guide presents a high-level ‘go to’ document with coherent guidelines, which engineers can utilize in making decisions regarding lost circulation treatments in the Shuaiba formation. The part also employed a thorough literature review to identify relevant information that could be included in developing the screening guide.

This section will summarize the required treatments for each type of the lost circulation. More than 300 wells have been analyzed to figure out the successful remedies for each type of the losses, and these treatments are classified by relying on the mud losses classifications to get effective remedies, minimize cost, reduce non-productive time, and avoid unwanted consequences due to inappropriate actions. A lost circulation screening criteria is presented for this formation based on the historical mud loss and lost circulation problems, materials used to mitigate the problems, and potential solutions found by this study. In addition, practical field information from a range of sources was reviewed and summarized to develop an integrated methodology and flowchart for handling lost circulation events in the Shuaiba formation. The economic evaluation is conducted for partial, severe, and complete losses. Table 9 is only example to show the results of the economic evaluation for complete losses treatments with their probabilities. Figure 16 provides guidance for drilling through the Shuaiba formation and handling loss circulation through this formation.

Table 9. Complete Losses Economic Calculations and Probabilities

Treatment Name	**Required Addition, kg/m^3**	**Cost ($/m^3)**	**Waiting Period (hrs)**	**NPT Cost ($/hr)**	**Total Cost ($)**	**Success (%)**	**Fail (%)**
Cement Plug	1176	374	18	1500	27374	45	55
H.V Mud +Cement Plug	Bentonite (100), Cement (1029)	406	20	1500	30406	80	20
DOB Plug	The formula for 1 m^3 Oil base 0.70 m^3 Bentonite 800 kg	604	10	1500	15604	75	25
DOBC Plug	The formula for 1 m^3 Oil base 0.72 m^3 Bentonite 450 kg Cement 450 kg	646	12	1500	18646	70	30

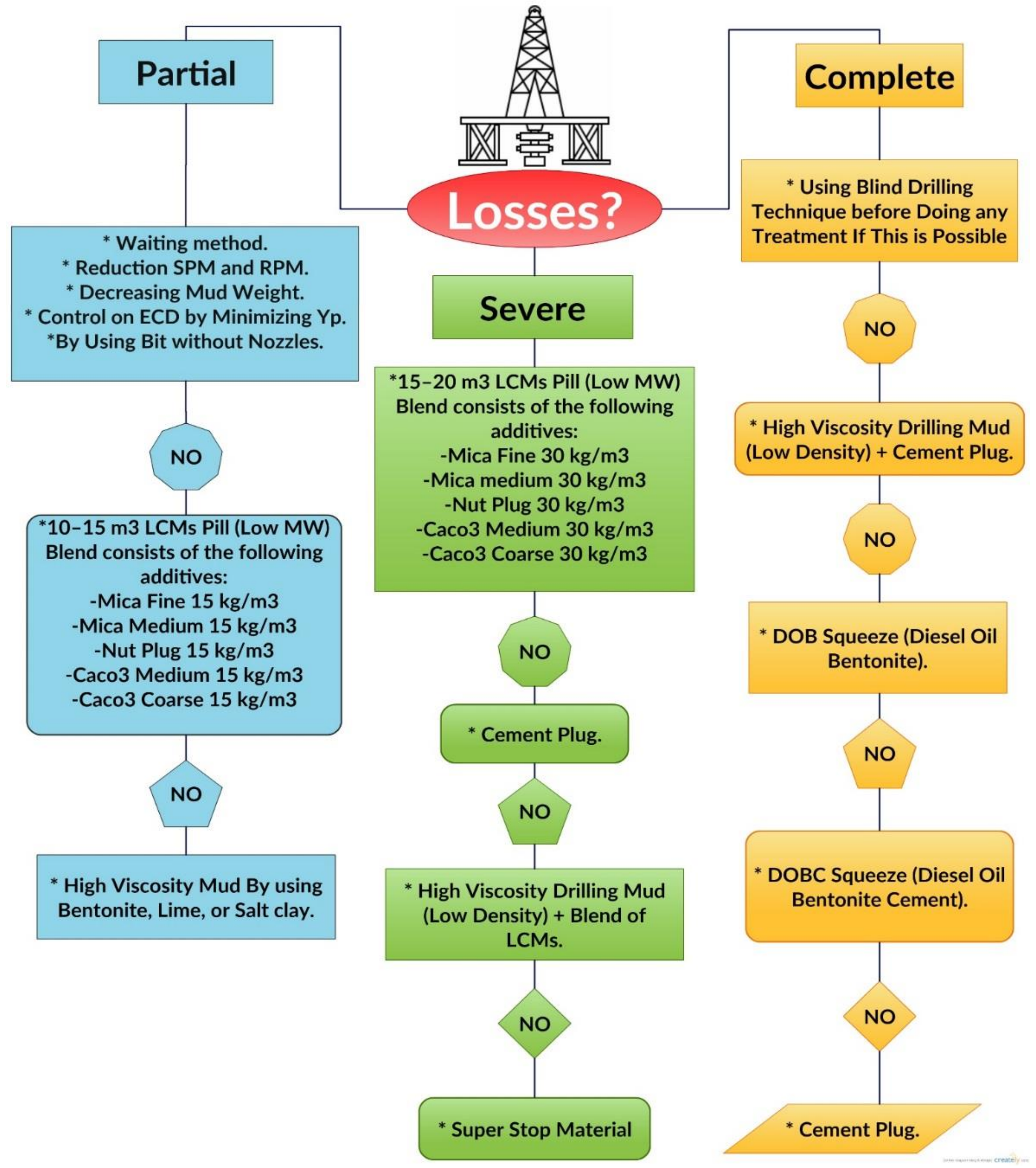

Figure 16. Treatment Strategy to the Shuaiba Formation

7. GENERALIZATION OF THE VOLUME LOSS MODEL FOR THE SHUAIBA FORMATION

The above three statistical models have been generalized to come up with one equation for Shuaiba formation (only volume loss equation) to predict the mud losses anywhere in Basra's oil fields. ROP model (Equation 6) has been substituted in ECD model (Equation 5), and then ECD model has been substituted in volume loss model (Equation 4), Figure 17 illustrates the implemented procedures for the generalization of volume loss model.

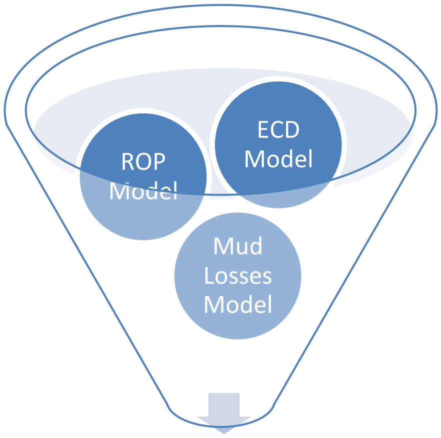

Figure 17. Generalization of Volume Loss Model for the Shuaiba Formation

Based on MW, Q, RPM, WOB, and Yp a model to estimate the volume loss was developed to estimate the loss volume before drilling the Shuaiba formation in Basra's oil fields. The volume loss model developed is expressed by Eq. (7):

$$\text{Mud Loss} = -1131.38 + 908.912 * MW - 0.001354 * Q + 0.100788 * RPM + 3.4849 * WOB + 3.982 * Yp \quad \ldots\ldots (7)$$

8. CONCLUSION

This paper presents a comprehensive statistical study and sensitivity analysis models for more than 300 wells drilled in the 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, ECD, and ROP.

The three models developed in this study can be used to estimate 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.

Based on this study, the following conclusions are made:

1. This paper provides models to help estimate mud losses prior to drilling based on key drilling parameters. As a proactive approach, the key drilling parameters can be limited to mitigate losses. If the proactive approach failed to mitigate losses, a lost circulation treatment strategy is provided so that the drilling personnel can easily follow this strategy to stop mud losses to minimize NPT and cost.
2. This is the first study utilized big data and multiple linear regression to estimate mud losses prior to drilling and create treatment strategy for each of losses in the Shuaiba formation. This methodology can be adopted and utilized in any formation that is suffering from lost circulation globally if the there is enough data available about that formation.

3. Three models developed in this study that can be used to estimate ROP, ECD, and mud losses prior to drilling the Shuaiba formation, Iraq or any formation that has the same formation properties as the Shuaiba formation.
4. The highest probability of success treatment should be used to treat the mud losses even if it is not the cheapest to avoid the repetition of treatments which reduces the NPT. Using a low-probability of success treatment may not be effective and the use of multiple treatments may be required, even if it is cheaper than other treatment but the NPT will be higher which increases the cost.
5. The first treatment that should be used to treat complete losses in the Shuaiba formation is blind drilling. This method is dangerous and should be applied carefully in the field.
6. The first treatment that should be used to treat partial losses is the waiting method. If it fails, then use the recommended treatments in the flowchart.
7. The first treatment that should be used to treat severe losses is pill of LCM (High Concentration). If it fails, then use the recommended treatments in the flowchart.
8. Key drilling parameters that should be used to drill the Shuaiba formation are identified and summarized. Lost circulation can be avoided or mitigated when using these parameters.
9. Treatment strategy for partial, severe, and complete losses for the Shuaiba formation are summarized in a flowchart. This flow chart should be used to treat the mud losses in the Shuaiba formation depending on the type of mud losses.

NOMENCLATURE

Symbol	**Description**
D	Depth
DDR	Daily Drilling Report
DOH	Diameter of Open Hole
ECD	Equivalent Circulation Density
FP	Fracture Pressure
Ft/min	foot per minute
FWB	Fresh Water Bentonite
gm/cc	gram per cubed centimeter
HP	Hydrostatic Pressure
H. V	High Viscosity
Ib/bbl	pounds per barrel
Ib/ft^3	pounds per cubed feet
in	Inch
Kg/m^3	Kilogram per cubed meter
LCMs	Lost Circulation Materials
L/min	Litter per minute
m	meter
m^3/hr	cubed meter per hour
MW	Mud Weight
NPT	Non-productive Time

O.E.D.P	Open End Drill Pressure
ppg	pounds per gallon
PP	Pore Pressure
Q	Flow Rate
ROP	Rate of Penetration
RPM	Revolutions per Minute
SPM	Stroke per Minute
TFA	Total Flow Area
WOB	Weight of Bit
WOC	Waiting of Cement
WON	Without Nozzles
Yp	Yield Point Viscosity
$	Dollar

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SECTION

2. CONCLUSION

Based on this study, the following conclusions were made:

1. Successful control or treatment of lost circulation depends on several factors such as borehole temperature, pressure, lithology, type of losses, accurate calculations depth, and size of the thief zone.
2. There are no guaranteed methods for solving lost circulation problems entirely, but a lot of approaches can be used to prevent its occurrence, especially those that occur via induced fractures when drilling formations that are prone to losses.
3. Practical guidelines have been developed that when used with the accompanying flow chart will serve as a quick reference guide to prevent and minimize the problem of lost circulation while drilling in Basra’s oil fields.

VITA

Abo Taleb Tuama Al-hameedi was born in Thi Qar, Iraq. He received his bachelor degree in Petroleum Engineering from Baghdad University, Baghdad, Iraq in 2006. After graduation, in October 2007, Abo Taleb joined South Oil Company as trained engineer. He worked as a mud engineer in various oil field like South Rumaila, Zubair, Nahur Umar, and Allhis. He also worked in Weatherford Company as mud engineer. In February 2013, he was a scholarship recipient of the ExxonMobil Iraq Training, Technology & Scholars Program, and a fully funded scholarship program administered by the Institute of International Education (IIE) to study Master's degree in Petroleum Engineering. He started at Missouri University of Science and Technology during the fall semester of 2014 to work under the supervision of Dr. Shari Dunn-Norman as a graduate student, and he got his master degree in 2016. His dissertation topic was about lost circulation mud to study this issue with field cases. He received his Ph.D. of Science degree in Petroleum Engineering from Missouri University of Science and Technology in December 2018.

His research interests was in avoiding and mitigation of lost circulation problem, a comprehensive study for this issue with application in the Basra oil field, Iraq and other historical cases in international oil fields have been demonstrated.