Chair of Drilling and Completion Engineering

Master Thesis

Case Study: Stuck Pipe Analysis for Deviated Wells

Written by:
Gergely Holoda, BSc
1335417

Advisor:
Univ.-Prof. Dipl.-Ing. Dr.mont. Gerhard Thonhauser
Ass. Prof. Dipl.-Ing. Dr.mont. Michael Prohaska-Marchried

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AFFIDAVIT

I hereby declare that the content of this work is my own composition and has not been submitted previously for any higher degree. All extracts have been distinguished using quoted references and all information sources have been acknowledged.

Date

Signature

Kurzfassung

Das Feststecken von Bohrgestänge, hierbei vor allem das Feststecken durch Druckunterschiede ist wahrscheinlich das größte Problem bei Tiefbohrungen im Bezug auf Zeit,- und Kapitalverlust. Wenn das Bohrgestänge erst einmal feststeckt muss ein sehr zeit,- und kostenintensives Befreiungsmanöver angewendet werden um das Gestänge wieder in einen frei beweglichen Zustand zu versetzen.

Die Firma die die Daten für diese Diplomarbeit zur Verfügung gestellt hat, musste drei Fälle von feststeckendem Gestänge erdulden. Es dauerte ingesamt 10 Tage um das Bohrgestänge wieder frei zu bekommen, deshalb ist es essenziell die Ursache dafür zu finden. Die Firma nimmt an dass es eine Verbindung zwischen diesen Problemen gibt und das Ziel dieser Diplomarbeit ist es, diese(s) Problem(e) zu finden.

Die Arbeit begann mit einer Recherche durch allmögliche Literatur aus der Erdöl/Erdgas – Industrie. Danach wurde eine Zusammenstellung der Ursachen für die Druckunterschiede die zu einem feststecken des Gestänges führen angefertigt. Jeder Grund wurde ins Detail begutachtet und nach Lösungen gesucht, um das Feststecken zu verhindern.

Diese Arbeit enthält eine durch Computersimulation gestützte Vorhersage mit künstlicher-neuronaler Netz-Modellierung um festzustellen ob die anwendbaren Modifikationen zielführend sind und ob das Festecken in der gleichen Situation nicht mehr passieren würde. Das Modellieren mit Künstlich-Neuronalen-Netzwerken ist ein sehr leistungsfähiges Datenmodell das die Fähigkeit besitzt, sehr komplexe input und output Daten zu erfassen und wiederzugeben. Der Beweggrund ein solches System zu entwickeln, stammt aus dem Verlangen ein künstliches System zu erstellen dass „intelligente Aufgaben“ ausführen kann, ähnlich dem Menschlichen Gehirn.

Die wirkliche Leistung und Vorteile dieser neuronalen Netzwerke liegt in deren Fähigkeit lineare und nicht-lineare Zusammenhänge wiederzugeben und in ihrer Fähigkeit, diese Zusammenhänge direkt aus dem Datenmodell zu lernen, das gerade modelliert wird.

Um die nötigen Fähigkeiten zu besitzen ein so leistungsfähiges Datenmodell zu verwenden war der erste Schritt die Parameter festzulegen, die der Autor gerne in seinem Modell anwenden würde. Dies war eine sehr komplexe Aufgabe da nicht alle dafür notwendigen Daten vorhanden waren. Manche mussten mit Hilfe anderer zugänglicher Daten berechnet werden.

Das erstelle Netzwerk bestand am Ende aus 17.406 Datensätzen, von denen 20% verwendet wurden um das Modell zu testen. Die Ergebnisse der Testphase ergaben 0.0575% falsche Vorhersagen, dementsprechend war die Vorhersage (Simulation) ziemlich genau.

Während dem Analysieren von Fällen in denen das Bohrgestänge stecken bleibt, wurden Faktoren festgestellt, die das Festecken durch Druckunterschiede (im Bohrloch)

beeinflussen. Neben anderen Faktoren waren dies hauptsächlich die Trajektorie des Bohrlochs, das angewendete Programm zur Bohrspülung, die Zusammensetzung (Rezept) der Bohrspülung, das Strömungsprofil, der Bohrklein-Abtransport und die BHA (Bottom Hole Assembly/ Bohrlochausstattung/ also das Zeug das zum Bohren gebraucht wird (Meisel, Motor, Gestänge, Casing).

Die angewendeten Verbesserungen wurden schließlich in das Datenmodell eingegeben und für die oben erwähnten drei Fälle Vorhersagen gemacht. Das neuronale Netzwerk Modell sagte für alle drei Fälle eine Situation hervor in dem das Bohrgestänge nicht stecken bleiben sollte, also kann festgehalten werden dass die Ursachen für das Feststecken gefunden wurden.

Abstract

Stuck pipe problems, within that, differential sticking problems is probably the greatest drilling problem worldwide in terms of time and financial costs. If once the drillstring stuck, a timely and costly freeing procedure need to regain the moving ability.

The company supporting this thesis provided data, brooked three differential sticking in the same area. To free the pipe, took more than 10 days overall, so finding the reasons is essential. The company assumed that there is a connection between these problems, and the aim of this thesis is to find it or them.

Work started with literature review from all over the industry's history, and then a summary was made of the influencing factors of differential sticking, introduced every one of them in detail and how could modify them to avoid sticking.

The thesis contains a computational prediction with neural network modeling to help to prove that the applicable modifications were right, and the sticking would not have occurred in the same situation anymore. Neural network modeling is a powerful data model that is able to capture and represent complex input-output relationships. The motivation for the development of neural network technology stemmed from the desire to develop an artificial system that could perform "intelligent" tasks similar to those performed by the human brain. The true power and advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their ability to learn these relationships directly from the data being modeled.

To able to use this powerful data model, the first step was to determine the parameters, what the author would like to use in the model. It was a complex task, because not all of the necessary data was available, some of them had to be calculated from other available data.

The generated network at the end made up from 17406 datasets, of them 20% were used to test the model. The results of testing phase ended with 0.0575% bad prediction, so the prediction was quite punctual.

During the analysis of sticking situations, the factors, which influence differential sticking were investigated. Among other things well trajectory, mud program, mud formulation, flow pattern, solids control, BHA composition.

The applied modifications were finally put into the model and prediction was made for these cases. The neural network model predicted all cases as non-sticking situation, so it could stated that reasons of sticking were found.

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Abbreviations

API	American Petroleum Institute
BHA	Bottom Hole Assembly
BOP	Blowout Preventer
$CaCO_3$	Calcium Carbonate
D&S	Drill and Seal Procedure
DC	Drill Collar
DP	Drillpipe
ECD	Equivalent Circulation Density
GRN	Generalized Regression Net
Hi-Vis	High Viscosity Pill
HPHT	High Pressure-High Temperature
HWDP	Heavy Weight Drillpipe
ID	Inside Diameter
KOP	Kick-off Point
LCM	Lost Circulation Material
MD	Measured Depth
NaOH	Caustic Soda
OD	Outside Diameter
PCL	Pipe-conveyed Logging
PN	Probabilistic Neural Net
POOH	Pull Out of Hole
RIH	Run In Hole
ROB	Rotation Off Bottom
s.g.	Specific Gravity
TVD	True Vertical Depth
WOB	Weight on Bit

Nomenclature

$\bar{v}$	Mean velocity (ft/s)
∇p_{pp}	Pore Pressure Gradient (bar/m)
A_e	Effective area (in^2)
d_b	Diameter of ball in stickance test (in)
d_h	Diameter of the hole (in)
d_{op}	Outside diameter of the drillstring (in)
ECD	Equivalent Circulation Density (ppg)
f	Friction coefficient (-)
F_{po}	Pull-out Force (N)
g	Gravitational Constant (Nm^2/kg^2)
h_{mc}	Thickness of the mudcake (in)
L_{an}	Length of annular (ft)
L_{ep}	Length of the permeable formation (ft)
M_0	Torque to free the ball in stickance test(lbf/ft)
net_j	Interval activity of a neuron
N_{He}	Hedstrom number (-)
N_{Re}	Reynolds number (-)
o_j	Output of a neuron
p_{an}	Annular Pressure Loss (psi)
p_m	Hydraulic Pressure of Drilling Mud (psi)
p_{pp}	Formation Pore Pressure (psi)
Q	Flow rate (gpm)
s	Stickance
t	Time (s)
T_m	Temperature of the mud (°C)
v	Annular velocity (ft/min)
w_j	Weight of a neuron
x_j	Input
β	Thickness parameter of the mudcake (in/s$^{1/2}$)
Δp	Differential Pressure (psi)
μ_a	Apparent Viscosity (cP)
μ_p	Plastic Viscosity (cP)
ρ_m	Mud Weight (ppg)
τ_0	Shear stress of the mudcake (psi)
τ_y	Yield Stress (lb/100ft^2)

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1 Introduction

Stuck pipe is a general term used to describing the problem of losing the ability to move the drillstring. If once the drillstring stuck, a timely and costly freeing procedure need to regain the moving ability, stuck pipe problems can be classified into two main categories: mechanical and differential sticking. In this thesis, the author deals mainly with differential sticking. Prevention and prediction are quite hard, because there are not clear borders between stuck and non-stuck situations, but there are trends which we could reckoned with.

1.1 Scope of the Study

The company supporting this thesis provided data, had drilled more relatively shallow, deviated wells in Serbia. In some cases, there were different sticking problems. In these wells where problems occurred, the solution to free the pipe took more than 10 days overall, so finding the reasons is essential for the future drilling program of the company.

Because of the similar design of the wells and the similar area and geology, it can be assumed that the causes of the problems can be traced back to similar, maybe planning reasons. Main scope of this thesis to find that reason or reasons, and come up with a recommendation for drilling of similar wells.

Tasks during the project:

- Find relationship between the problems, if there is any.
- With the analysis of the given data, studying the geological environment and redesign of the problematic wells, find out the source of the problems.
- Using the generated detailed information of the problem causes and the obtained knowledge from literature review, come up with recommendation for future work.

Figure 1: Position of the three well in the map of Serbia[1]

1.2 Structure of thesis

In this chapter – Introduction – the author describes the base situation for the case study, specifies the structure of the thesis, and gives a short introduction of stuck pipe problems.

The second chapter contains the literature review part of this thesis, the short overview of the most relevance papers of the literature what could help to write the thesis.

The following chapters includes the theoretical background of differential sticking, the influencing parameters, and the base description of the neural network modeling.

Chapter 5 and 6 is the main part of the thesis, presents the analysis of the given data, contains the description of the neural network model.

The last chapter presents the results, the conclusions and recommendations for future work.

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[1] Source of the original outline map: EnhancedLearing.com. 2015.
http://www.enchantedlearning.com/europe/serbia/outlinemap/ (accessed 03 September 2015)

1.3 Stuck Pipe Problems

During drilling operations, a pipe is considered stuck if it cannot be freed from the hole without damaging the pipe, or without exceeding the drilling rig's maximum allowed hook load.[1]

Complications related to stuck pipe can account for nearly half of the total well cost, making stuck pipe one of the most expensive problems that can occur during a drilling operation.[2] Various industry estimates claim that stuck pipe costs may exceed several hundred million US dollars per year. Stuck pipe is often associated with well control and lost-circulation events.

As it was mentioned above, stuck pipe problems can be classified into two categories: mechanical sticking and differential sticking. This classification is based on the physical mechanism what causing the problem.

We are facing with mechanical sticking, if the pipe movement is prevented by mechanical causes. The most common causes of mechanical sticking are:

- Accumulation of cuttings
- Borehole instability (shale swelling)
- Reactive formations
- Key seating
- Junk in the wellbore

Freeing mechanically stuck pipe can be performed in a number of ways, depending on what caused the problem, but in general, the most appropriate way is to remove the mechanical obstacle. This can be done for example with circulation (cutting accumulation), increasing mud weight (reactive formation) or fishing operation (junk).

1.3.1 Differential Sticking

Differential sticking is one of the most common causes of pipe stuck, and it is probably the greatest drilling problem worldwide in terms of time and financial cost.[3] It can happen when

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[1] PetroWiki. 2015. Stuck Pipe. 26 June 2015.
http://petrowiki.org/Stuck_pipe (accessed 31 August 2015).

[2] Ottesen S., Benaissa S., Marti J. „Down-Hole Simulation Cell for Measurement of Lubricity and Differential Pressure Sticking”. Presented at SPE/IADC Drilling Conference, Amsterdam, The Netherlands, 9-11 March, 1999. SPE-52816-MS.

[3] Schlumberger Oilfield Glossary. 2015. Differential Sticking,
http://www.glossary.oilfield.slb.com/en/Terms/d/differential_sticking.aspx (accessed 02 September 2015).

there is a differential pressure pushing the drillstring (or the casing, or the logging tool) into filter cake of a permeable formation, the drillstring becomes embedded in the mudcake and stuck, as can be seen in Figure 2.[1]

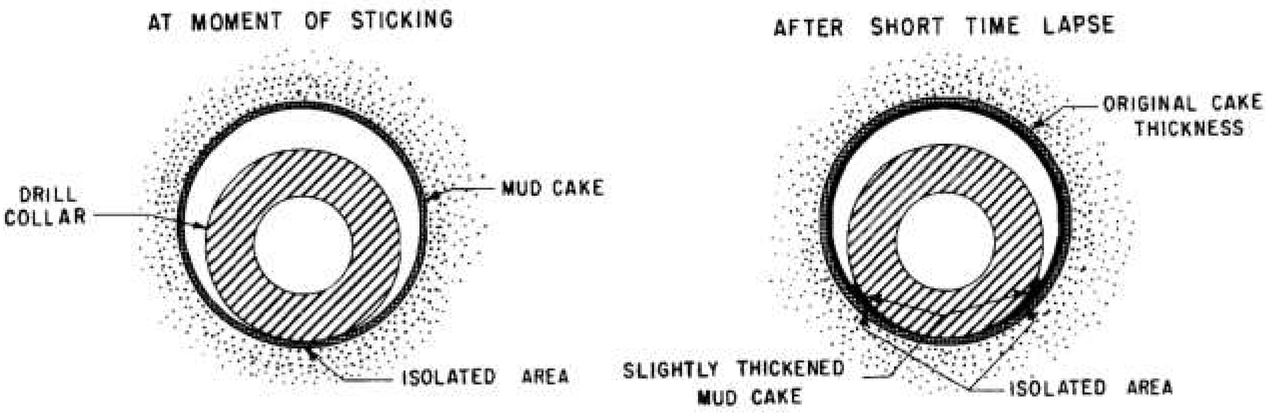

Figure 2: Mechanism of Differential Sticking[2]

Differential sticking can only take place across permeable rock formations, where a mud filter cake builds up. Generally, differential sticking also only occurs when the drillstring is stationary. If the differential stuck exists, the drillstring cannot be moved or even rotated, but mud circulation is still possible, because there is enough space in the wellbore for mud flowing.

If once the drillstring have stuck differentially, there are some common filed practices to free the string[3]. The three main categories of them are:

- Reduction of the hydrostatic pressure of the mud
- Oil spotting around the problematic section of the drillstring
- Washing over the stuck pipe

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[1] Reid P.I., Meeten G. H., Way P. W., et al. 2000. „Differential-Sticking Mechanisms and a Simple Wellsite Test of Monitoring and Optimizing Drilling Mud Properties". SPE 64114-PA. *SPE Drilling & Completion,* **15** (2): 97-104.

[2] Helmick W. E. And Longley A. J. 1957. Pressure-differential Sticking of Drill Pipe and How It Can Be Avoided or Relieved. Presented at the spring meeting of the Pacific Coast District, Division of Production, Shell Oil Company, Los Angeles, California, USA, May 1957. API-57-055.

[3] PetroWiki. 2015. Differential Sticking. 26 June 2015. http://petrowiki.org/Differential-pressure_pipe_sticking (accessed 02 September 2015).

2 Literature Review

When the literature research part of this thesis was done, the author had followed a chronological order from the oldest paper to the most recent ones, to follow the development of industry in this topic with time.

Pressure-differential Sticking of Drill Pipe and How It Can Be Avoided or Relieved[1]

The oldest paper what was read read was written in 1957. At this time, people in the industry know little about differential sticking, but they started to deal with the problem, because it was responsible for stuck problems in some cases while they drilled through depleted zones.

According to the knowledge of that time, only drill collars were stuck usually, if the pressure difference was big enough. In this era primarily vertical wells during the drilling of depleted zones showed this problem.

The authors of the paper constructed the first "Pressure-differential Sticking Test Apparatus", which was capable to model the sticking of the drill pipe in high differential pressure environment. They could rotate the "string", circulate the mud, and make a mud cake. They made numerous different tests, which were different in applied pressure difference and static time of the string (they called it "set time"), and the necessary pull-out force were recorded for every case. Later on, they have investigated the popular freeing technique, the oil-spotting.

From the results of their research, they could come up with some extremely important conclusions. One important observation was made that regardless of set time the pull-out force could always be lowered by reduction of the differential pressure, i.e. the force that holds the drill pipe against the wall is proportional to the differential between the hydrostatic pressure of the drilling mud and the formation pore pressure. The total force which is required to free the pipe is depends also on the pipe-to-hole diameter ratio and the rate of thickening of the cake. They found that there are two ways to release the pipe: reduce the hydrostatic head or spotting oil to wet the steel.

In the other examination, they found that the oil spotting method could be more efficient if they prepare the steel by making it more easily oil-wet. They accomplished it by two methods: coat the pipe to have greater affinity for oil, or add an agent to the oil. With these methods, they could achieve a massive reduce in the required time to free the pipe compared to the untreated oil-spotting technique. However, as they pointed out, the oil-spotting could be unsuccessful in field environment, because there could be channeling or other failure to reach the problematic zone.

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[1] Helmick W. E. And Longley A. J. 1957. Pressure-differential Sticking of Drill Pipe and How It Can Be Avoided or Relieved. Presented at the spring meeting of the Pacific Coast District, Division of Production, Shell Oil Company, Los Angeles, California, USA, May 1957. API-57-055.

So, as they wrote: the best method to cure the problem of differential sticking is to prevent it. In their recommendations, the following were included: use better muds, reduce pipe-to-hole diameter ratio and use of drill-collar stabilizers

A Field Case Study of Differential-pressure Pipe Sticking[1]

This paper was one of the first papers that have done field case analyses of differential-pressure sticking. The author investigated the success ratios of oil spotting release attempts. In this study, 310 fluid spotting applications was analyzed. The author got some important results. The greatest possibility of pipe sticking occurs at relatively shallow depths and not at the deepest formations. It may seem straightforward, but makes the well design more difficult.

Out of the 310 cases, only 44% were successful. This is correlate with the statement of the previous paper by Helmick and Longley, what stated that channeling and the improper amount of spotting fluid could undermine the success of the spotting operation. In the author's opinion, spotting fluid success is related to the volume of fluid used to effect pipe release. After a fluid has been spotted within the borehole, time is necessary to effect a release of the stuck drillstring. The mean of the investigated cases was more than 6 hours to release the pipe after the fluid has been spotted.

Adams' research has found an interesting fact, which is contrary with the previously published papers, that 18 cases of 32 stuck situations were in the drill pipe section, and only 4 (1/8th) were in drill collar zone. He explained this with the following:

> "Due to the small annular clearance at the collar region, the drilling fluid may exhibit turbulent characteristics and tend to minimize filter-cake buildup, a necessity in differential-pressure pipe-sticking."

From this statement, it is clear that the pattern of the fluid flow could be determinative factor.

Optimal Applications Engineering and Borehole Stability Analysis Avoids Differential Sticking and Leads to Successful Openhole Completion of North Sea Horizontal Well[2]

This paper describes how to manage drilling of a long-reach horizontal well in a classic depleted reservoir. The situation involves high risk in term of differential sticking. The paper

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[1] Adams N. 1977. A Field Case Study of Differential-pressure Pipe Sticking. Presented at the 52nd Annual Fall Technical Conference and Exhibition of the SPE, Denver, Colorado, USA, 9-12 October 1977. SPE-6716-MS.

[2] Gibson M. T. And Tayler P. J. 1992. Optimal Applications Engineering and Borehole Stability Analysis Avoids Differential Sticking and Leads to Successful Openhole Completion of North Sea Horizontal Well. Presented at the 67th Annual Technical Conference and Exhibition of the SPE, Washington, DC, USA, 4-7 October 1992. SPE-24615-MS.

covers three main topics, namely borehole stability analysis to avoid differential sticking, contingency planning in the event of sticking and openhole completion. From these the first two are interesting in the point of view of this thesis.

Drilling through a depleted reservoir it is very important to use an optimal mud weight in order to assure that the resulting well pressure is high enough to keep the borehole stable and low enough to minimize the risk of differential sticking. The minimum mud weight is determined by the three main in-situ stresses: the vertical, the maximum horizontal and the minimum horizontal stresses. (And not by the pore pressure as usual, because it is very low.)

In terms of drilling mud there are other several parameters what are important outside of mud weight. In their opinion, rheology is maybe the most important. They designed for laminar flow to prevent leak-off in the problematic depleted zone. Weighting agent, oil-water ratio and formation damage was also calculated, and they specified that one centrifuge had to run constantly.

When they planned the drilling operation, they also invested a lot of attention into BHA design. A massive reduction in risk of differential sticking could be achieved by using special profile drill collars, steerable motors with integral offset and computer software to optimize BHA string. The conclusions were that the modifications in the designing process were successful because there was not a single sticking in the examined period.

In the contingency planning section, they had two plans. The first is slightly similar to the conventional oil spotting method, but instead of oil they use acid. Spotting a Hydrochloric/Hydrofluoric acid mix would dissolve much of the filter cake. They determined one pill (equals 1000 gallons of acid) for one treatment, and materials were kept on board for three pills. The other plan was to reduce the hydrostatic pressure in the wellbore by injection of Nitrogen gas into it.

Three History Cases of Rock Mechanics related Stuck Pipes while drilling Extended Reach wells in North Sea[1]

Out of the investigated three cases one was related to differential sticking. The problem in this case was depletion. There are three permeable layer in a row at this field, but the level of depletion is different, so they could not lower the weight of the mud to the proper level to avoid sticking. From the previously drilled wells, the depleted pressures were not perfectly known, and there was a problem because the bad control of the mud filtrate which cause that the mud cake was 7 mm thick. Moreover, there was a direction survey, while the string was static for 15 minutes. These three factor, namely the too high differential pressure, the thick mud cake, and the long static time leaded to sticking.

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[1] Charlez P. A., Onaisi A. 1998. Three History Cases of Rock Mechanics related Stuck Pipes while drilling Extended Reach wells in North Sea. Presented at the SPE/ISRM Eurock ’98 in Trondheim, Norway, 8-10 July 1998. SPE-47287-MS.

The authors proposed the following possible solutions:

- The duration of the non-rotating periods has to be minimized.
- The filtrate has to be controlled consequently by the mud engineer, and if necessary, the mud filtrate can be decreased by charging the mud with polymers.
- If planning an operation through depleted reservoirs the degree of depletion should be taken into account to avoid high differential pressures in the borehole.

Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling[1]

This paper deals with prediction of pipe sticking using two different methods, fuzzy logic and neural network modeling. The authors generated 185 datasets from drilling and mud reports with 18 variables, such as depth, flow rate, bit size, yield point, etc. and classified into three groups, mechanical, differential stuck and non-stuck cases.

Firstly, they used discriminant analysis to generate a predictive model of group membership. Two discriminant functions was built and the overall correct classification was 98.4%. Then they made five dimensionless groups from the 18 variables for the fuzzy logic and neural network, to make the prediction as reliable as it could be.

Fuzzy logic is an analytical statistical technique, which uses the error of the datasets to complement the discriminant function classification. Neural network is a powerful data modeling tool that is able to capture and represent complex input-output relationships. The basic structure is neural network is a computer representation of a biological neuron that is interconnected with other neurons (like in human brain).

The fuzzy logic and neural network models were used as quick evaluation tools to predict and classify sticking occurrences into the three groups. In the study, the neural network model had much less misclassification than the fuzzy logic model.

Design Methodology and Operational Practices Eliminate Differential Sticking[2]

This paper describes a summary from techniques to avoid differential sticking (they called it Stuck Pipe Avoidance Practices) and presents the results from a five-year period. Changes were made in BHA design, fluid design, real-time cake shear strength recognition and real-time remediation practices.

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[1] Murillo A., Neumann J., Samuel R. Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling. 2009. Presented at the 2009 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA 4-8 April 2009. SPE-120128-MS.

[2] Dupriest, F. E.; Elks Jr., W. C. and Ottesen, S. 2010. Design Methodology and Operational Practices Eliminate Differential Sticking. Presented at the 2010 IADC/SPE Drilling Conference and Exhibition held in New Orleans, Louisiana, USA, 2–4 February 2010. SPE-128129-MS

Firstly, they introduced the known theories and practices what are in daily use in the field. Especially covered the topic of the cake shear strength and the time dependency of the pullout force.

After that, the authors started to describe the different topics of the Stuck Pipe Avoidance Practices. They had two thematic groups of practices. The first group is linked to contact area between the formation and the drillstring, and the second is linked to cake morphology and fluid design, and there is an extra recommendation that try to minimize the still-pipe time.

In the first group what collects the techniques to minimize the contact area there are 5 techniques. They started with the most notorious, the drill collars. In their practice, they propose to use Heavyweight Drillpipes instead of drill collars. As they explained, in the most cases there is possible to apply enough WOB with HWDPs, particularly in deviated wells. Linked to this, they went a step further, and recommend to change the HWDPs to normal drill pipes in highly deviated and horizontal sections. With these changes the contact area could be reduced to 1/5. They called attention the danger of slick assemblies and wear groove. Similar to DCs, drilling jar also also has a high risk potential. To avoid sticking they recommend to use standoff subs with jars.

To prevent differential sticking, drilling mud has to complete two criterions: it should be as thin as it can be, and has a slow rate of filtrate loss. They criticize the API's procedures to measure filtrate loss because in their opinion, these are unreliable in higher permeability conditions. Then they introduced an interesting technique to prevent sticking while drilling in depleted zones, called “Drill & Seal Procedure”. The process is extremely effective in avoidance sticking while logging. The procedure is the following:

> “In the Drill & Seal process, the stabilizers are used to ream the original cake in the presence of a pill that is rich in the appropriate blocking solids for the given formation, as well as filtration control material. The pill is pumped and timed to arrive at the bit as the next stand of drillpipe is drilled down. As the pill enters the annulus, the pump rate is reduced to a very slow rate and the string is reciprocated and rotated as the pill is pumped up the annulus. As the stabilizers are rotated, they strip the original cake and the rich content of the D&S pill accelerates the fine particle selection process at the reexposed cake face.”

They report a surprising result. Against to the previous experiments, during the investigation there were more sticking when the operator used oil-based mud, than they used water-based mud. Finally, they mention that there is the possibility to reduce overbalance by lighten the mud weight, but as they wrote it is more dangerous than reduce the contact area, because higher mud weight could be necessary to control pore pressure or borehole stability.

The result of the investigation was that out of 3476 wells, drilled by 20 different teams there were only 3 stuck with compliant BHA and 17 stuck non-compliant BHA, so the practices are very effective in prevent of differential sticking.

Stuck Pipe Best Practices – A Challenging Approach to Reducing Stuck Pipe Costs[1]

This paper is a report of Saudi Aramco's new strategies to reduce the high number of differential sticking. The source of the problem is that the deeper reservoirs became economic due to the higher oil prices at the end of the 2000's and they had to drill through shallower depleted zones. The high number of sticking means that it cost to the company about 2 rig-years every year. Then they decided that it is necessary to improve the sticking statistics.

The work was done in four areas. The first one, of course collected the best practices for Stuck Pipe Avoidance, in term of well design and drilling operations. The next topic had a title of "Economics of Fishing versus Sidetrack", and it is covered the way how could they decide where is the optimal point to give up fishing and sidetrack the well. The third practice is about a Training Campaign to prepare the crew how to handle an incidental sticking in a proper way. They introduced a new certified course, what is valid for 2 years. The last point is "Reporting and Analysis". They made a reporting template which was extremely helpful in the investigation of sticking events, and the it helped to draw the conclusions.

Due to the new strategies the number of differential sticking problems decreased by 14% in 1 year and the stuck pipe frequency improved to 5 wells from 4 wells also in 1 year.

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[1] Muqeem M. A., Weekse A. E., Al-Hajji A. A. 2012. Stuck Pipe Best Practices – A Challenging Approach to Reducing Stuck Pipe Costs. Presented at the SPE Saudi Arabia Section Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia, 8-11 April 2012. SPE-160845-MS.

3 Theoretical Basics of Differential Sticking

In this chapter of the thesis there is an introduction of the theoretical background of differential sticking, what are the main driver factors and parameters and how the sticking could be prevented.

3.1 General Introduction

As it was mentioned in the introduction chapter, differential sticking can happen when there is a differential pressure pushing the drillstring into filter cake of a permeable formation, and the drillstring becomes embedded in the mudcake and stuck.

Thus, differential sticking has four criteria:

- High differential pressure in the wellbore
- Permeable formation
- Developed mudcake
- Static time while the drillstring not moving or extremely slow.

If one of the above not fulfilled, the drillstring won't stuck.

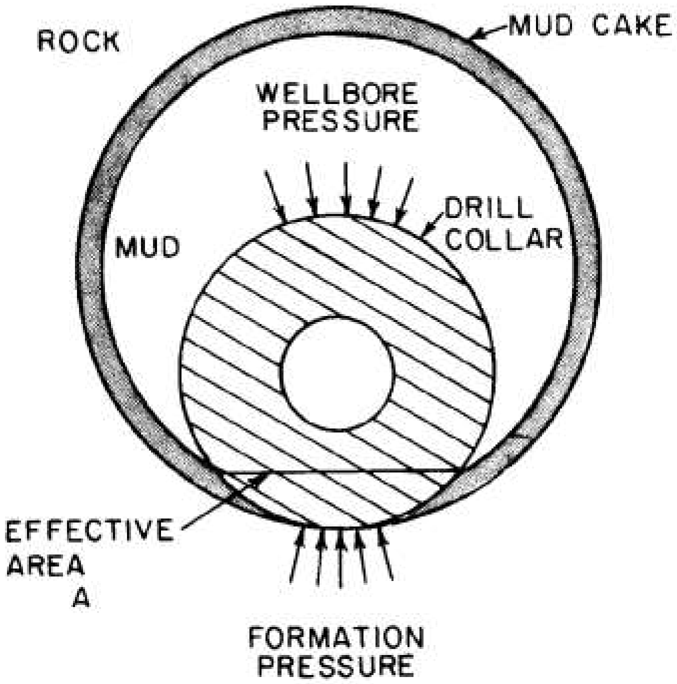

Figure 3: Criteria and mechanism of Differential Sticking[1]

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[1] Bourgoyne A. T., Millheim K.K., Chenevert M. E., Young Jr. F.S. 1986. "Applied Drilling Engineering". Richardson, Texas, USA: Textbook Series, SPE.

Of course, there are several other parameters which influences the differential sticking. For example, the most obvious the contact area. If we have slick drill collar in the string, it could be easily stuck because it has a greater diameter compare to the hole diameter, so the contact area between the string and the formation is big. But if we have a spiral collar it has much less contact area, because of the spirals and these help to prevent sticking (although the diameter ratio is the same).

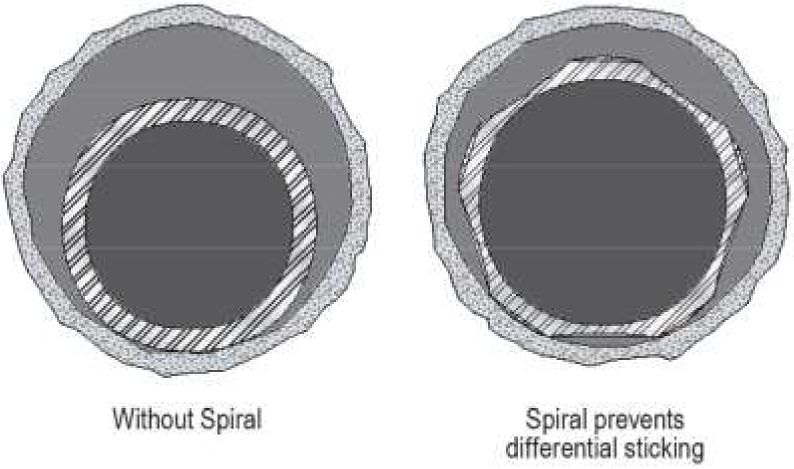

Figure 4: Spiral versus non-spiral drill collars[1]

The basic equation of differential sticking is the following, which describes the required force to free the string:

$$F_{po} = \Delta p A_e f \qquad \text{Eq. (1)}$$

Where F_{po} is the required force to pull out, Δp is the differential pressure, A_e is the effective area and f is the friction coefficient. As could be seen, the force is directly proportional to the differential pressure, the contact area and the friction coefficient. Differential sticking occurs when the force what is required to free the pipe exceeds the rig's maximum hookload capacity or the pipe's tensile strength.

3.2 Differential Pressure

One of the important driver factors for differential sticking, if not the most important, is the differential pressure. It can be expressed as:

$$\Delta p = p_m - p_{pp} \qquad \text{Eq. (2)}$$

---

[1] NOV. 2015. Drill Collars. https://www.nov.com/uploadedImages/Content/Segments/Wellbore_Technologies/Grant_Prideco/Drill_Collars/spiral-difference.jpg?n=3238 (accessed 07 September 2015).

Where *Δp* is the differential pressure, p_m is the hydraulic pressure of the mud and p_{pp} is the pore pressure.

To reduce the risk of the differential sticking should be sought to keep the differential pressure as low as possible. Naturally, we can not influence the reservoir’s pore pressure. The only way to control the differential pressure is leading through the mud weight.

In the designing process, drilling engineer determines the optimal mud weight for each casing section. The driver of the determination is mainly a special range between the pore pressure and the formation fracture pressure, called “mud window”. This mud window determines the number of the casing sections, and assigns the mud weights for this sections.

If we have to drilling through a depleted reservoir, mud weight window could suddenly expand, so the designed mud weight would be too high for this zone and this high differential pressure would be dangerous in term of differential sticking and also for lost circulation problems.

In the Figure 5, you can see a simple example of casing setting depth determination. The two situation is nearly the same, but in the right-hand site case there is a depleted zone at 2000m.

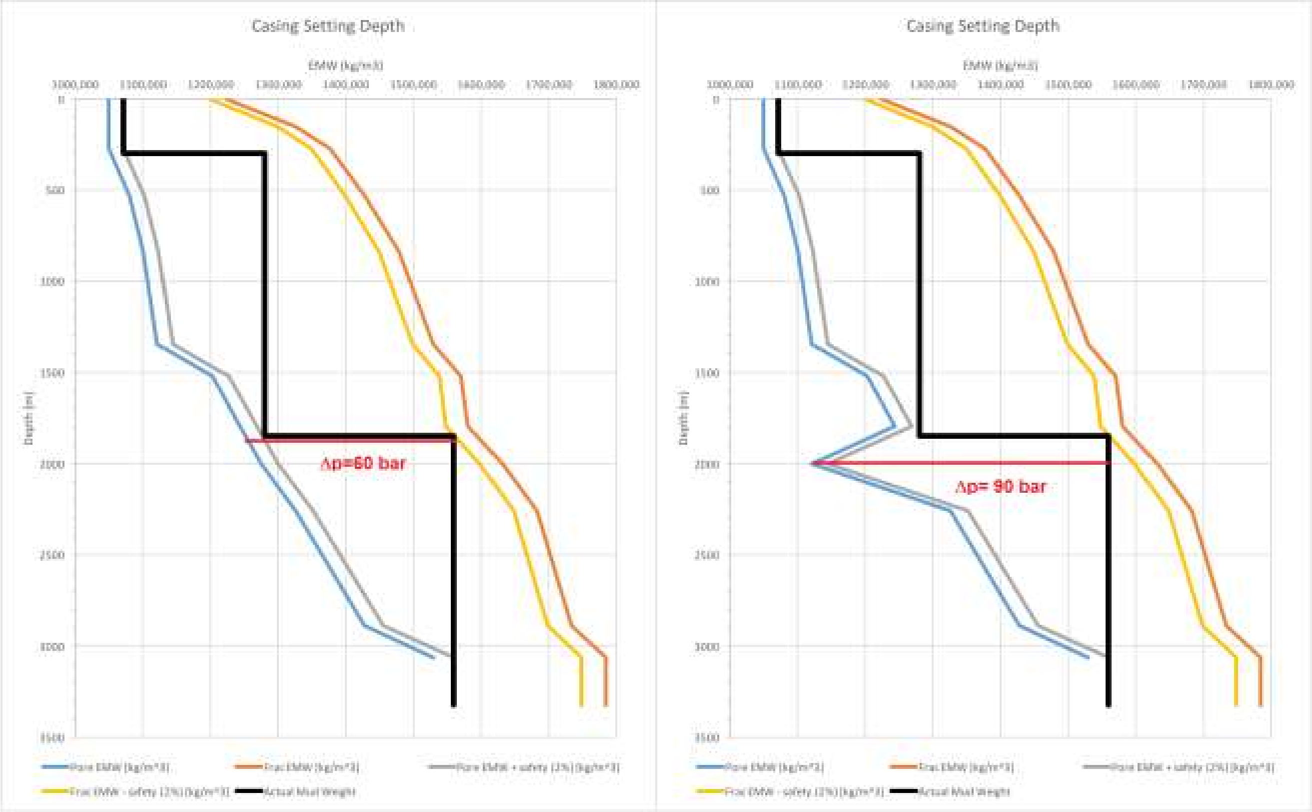

Figure 5: Example for dangerous depleted zone in casing setting design

Although there is a massive 33% increase in differential pressure, we can not keep the mud weight lower with this well plan, because it could cause well control issues.

Of course, we can design the well for this depleted zone to avoid high differential pressures, for instance if we stay on the previous example, as the following:

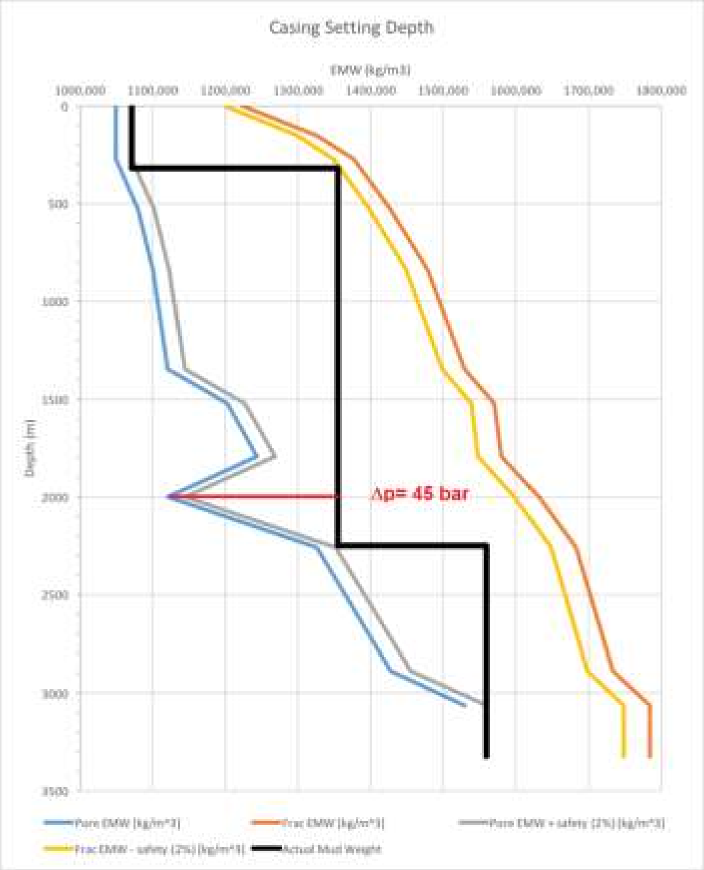

Figure 6: Casing setting design considering depleted zone

We could cut the magnitude of the differential pressure by the half. But in order to do we can do this, we have to know the exact pore pressures, what could be problematic in a depleted reservoir like this.

There is one extra factor that we have to calculate with, notably the borehole stability. If the hydrostatic pressure in the wellbore is too low, borehole collapse could occur. Prior to drilling in the reservoir there are stresses, called in-situ stresses. These stresses can be divided into three main components: the maximum horizontal stress, the minimum horizontal stress and the vertical (overburden) stress. If we know the in-situ stresses, the borehole breakdown pressure, thus the minimum mud weight could be determinate. However, the determination of the in-situ stresses is a difficult reservoir and geomechanical modeling process, but it could be done if every information is provided. So the successfully design of well through a depleted reservoir needs a cooperation between the reservoir and the drilling department.

As can be seen in the Figure 7, the maximum risk zones are perpendicular to the maximum horizontal stress. (In the Figure, the blue zones the most safety zones, and the red zones the most dangerous zones.) The maximum horizontal stress squeezes the borehole, and it will deform to the direction of the minimum horizontal stress, so the borehole will be elliptical and maybe it can not be interoperable anymore.

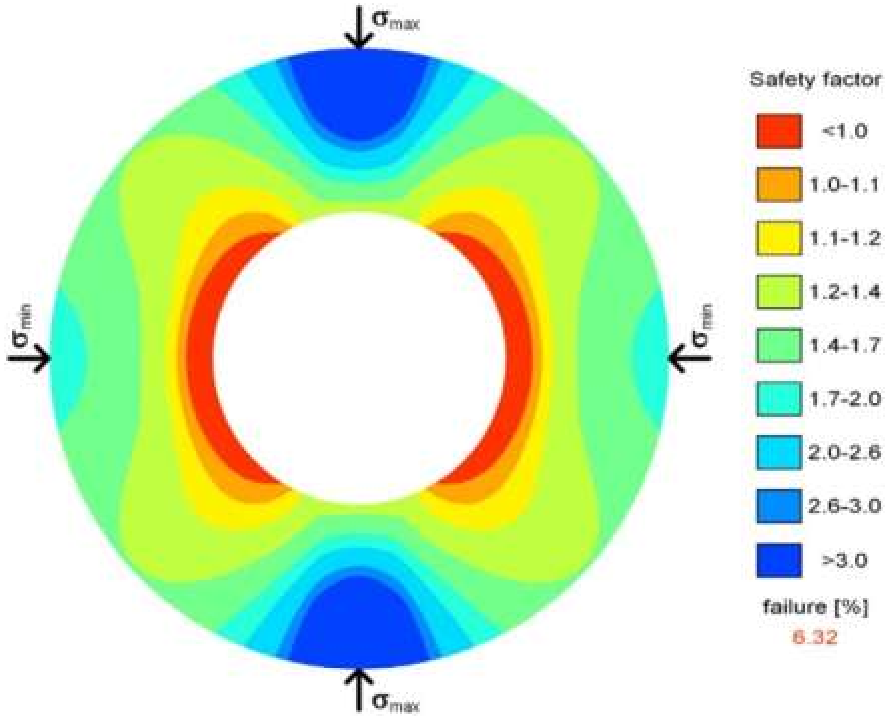

Figure 7: Borehole collapse risk zones[1]

The previously shown methods are used to prevent sticking, but if the differential sticking had occurred, there is still a fair solution to reduce the differential pressure. It is still valid that the reducing mud weight can happened with strictly considering well control and borehole stability issues.

If it is possible there are two ways for that in the literature. The simple method is reducing mud weight with mixing new, low density mud. The other way to reduce differential pressure is injection of nitrogen gas into the annulus through the choke or the kill line. Because the mud would be reverse circulated in the drillstring, it would be capable for reverse circulation.

3.3 Filter Cake

In contrast to the above described mud weight, we can control the mud composition and other properties of the mud in a widely scale. The desired filter cake would be thin to minimize contact area and have a slow rate of filtrate loss from the cake to the formation, so the increase in effective stress and shear strength would allow greater still-pipe time.

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[1] Dr. Ronald Braun Consultancy in Rock Mechanics. Borehole Stability.16.12.2014. http://www.dr-roland-braun.com/EN/evaluation/borehole_stability/main_frame_en.html (accessed 09 September 2015).

Properties of drilling mud which influences the risk of differential sticking:

- Mud weight (discussed in the previous subchapter)
- Mud solids content
- Generic mud type
- Specific mud formulation (additives, lubricants ad bridging particles)
- Fluid loss
- Filter cake quality[1]

Mud solids content: Drilling solids content in the mud is usually strictly prohibited because to maintain the optimal size distribution and plastic viscosity we have to know the exact properties of the mud, solids cause uncertainties. Solids control requires special attention is high differential sticking risk wells. Recommended practice in the industry to use at least one centrifuge constantly at rig site.

Generic mud type: We distinguish three main types of drilling muds: oil-based muds, polymer water-based muds and gel water-based muds. In general, the highest sticking risk is associated with gel water-based muds, and to lowest risk is paired with oil-based muds. The polymer water-based muds fall into between this two edge. The reason is because the oil-based muds have naturally thinner filter cakes than water-based muds, thus the contact area is less. But it is just a common truth, the sticking potential is greatly varying within a mud type, depending on the exact formula. For example, Dupriest et al highlighted that in their investigated period, there were all of the sticking problems occurred in oil-based mud. The reason for that could be that the most dangerous wells priori designed with oil-based mud.[2] Another problem is that oil-based is forbidden to use in many region, for example in most of Europe. For all the above reasons, generic type of mud is not essential question.

Specific mud formulation: Many studies have shown that the addition of certain lubricants to drilling muds will reduce the risk of differential sticking or if sticking still occur, reduce the force what is needed to free the string.[1] Lubricants could work to reduce sticking potential both in oil- and water-based muds.

The lubricant could work by one of the below mechanism, depending on the chemical composition:

- Coat metal surfaces thereby reduces the adhesion of steel to the filter cake

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[1] Reid P.I., Meeten G. H., Way P. W., et al. 2000. „Differential-Sticking Mechanisms and a Simple Wellsite Test of Monitoring and Optimizing Drilling Mud Properties”. SPE 64114-PA. *SPE Drilling & Completion,* **15** (2): 97-104.

[2] Dupriest, F. E.; Elks Jr., W. C. and Ottesen, S. 2010. Design Methodology and Operational Practices Eliminate Differential Sticking. Presented at the 2010 IADC/SPE Drilling Conference and Exhibition held in New Orleans, Louisiana, USA, 2–4 February 2010. SPE-128129-MS

- It could be built in the filter cake hence insures better fluid-loss properties,
- Or it could be built in the the filter cake to reduce the yield strength of the cake.

It is not excluded that several different of these mechanisms work together by one lubricant, moreover today's best lubricants could definitely do this.

Fluid loss: Flowing of the drilling fluid into the formation is undesirable in every well, but especially important to avoid it when there is a massive risk of differential sticking. If there is fluid loss to the reservoir in a differential sticking risky zone, the solid content of the mud will accumulate, and a thick mudcake formed what raises further the risk.

In order to restrain fluid loss, need to add some blocking agent. Blocking solids capable to prevent other solids entering from the formation and also the fluid phase flowing to the formation by blocking the pore throat openings. Usually, the blocking solid is barite, because it is easily accessible, relatively cheap and does its job well.

But in special cases, like very high permeability formations, barite is not effective anymore, because it is too small to block pore throat openings above 1 Darcy. Instead of barite, calcium carbonate or ground marble, or combinations thereof, is the proper choice in high permeability formations, where the differential sticking risk is naturally higher than low permeability formations.[1] The working mechanism of combination could be seen in Figure 8.

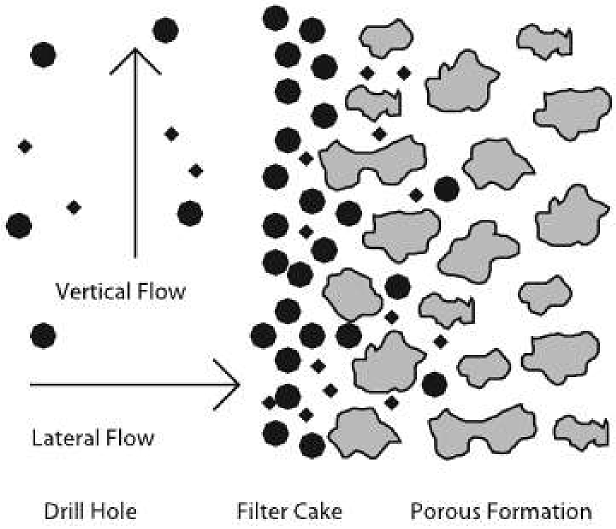

Figure 8: Fluid loss agent working mechanism[2]

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[1] Gibson M. T. And Tayler P. J. 1992. Optimal Applications Engineering and Borehole Stability Analysis Avoids Differential Sticking and Leads to Successful Openhole Completion of North Sea Horizontal Well. Presented at the 67th Annual Technical Conference and Exhibition of the SPE, Washington, DC, USA, 4-7 October 1992. SPE-24615-MS-

[2] Fink J. K. 2003. *Oil Fileds Chamicals.* First edition. Burlington, Massachusetts, USA: Elsevier Science.

Filter cake quality: Probably the most important of the mud factors. Filter cake quality is a complex factor, because it is influenced by all of the variables what were presented above.[1] Even so it is a very determinative property, a measurement of filter cake quality not a part of the standard API measurements. Hence, Reid et al. made a viable tester for it, called "Stickance Tester".

The schematic diagram of the Stickance Tester could be seen on the Figure 9. As the figure shown, the body of the tester is a mud filtration cell. In the cell, there is a steel ball what is lowered in mud, and the ball is connected to an electric torque gauge. The test is carried out by pressurizing and heating the mud to the desired values, then the filter cake built up around the ball. After that in every 5 minutes, the torque gauged is turned and the force which is required to free the ball is measured. The torque data what was got, could be plotted as a function of the time (actually, $t^{3/4}$). Usually, it delivers a straight line, and the slope of this line is defined by the differential sticking tendency, i.e. the stickance.

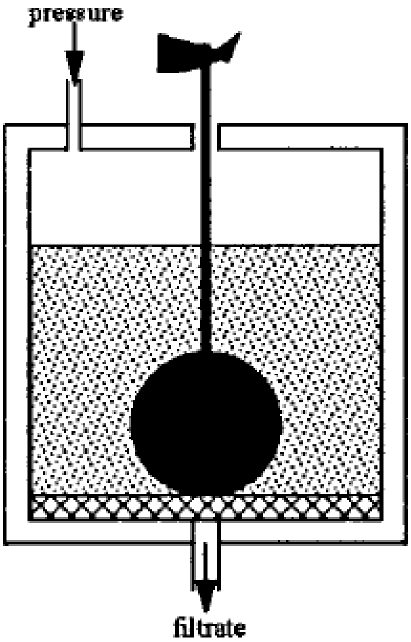

Figure 9: Schematic diagram of Stickance Tester[1]

The theory behind to test could be described with the following equation:

$$M_0 = \frac{2}{3}\pi d_b^{3/2}\beta^{3/2}\tau_0 t^{3/4} \quad \text{(Eq. 3)}$$

---

[1] Reid P.I., Meeten G. H., Way P. W., et al. 2000. „Differential-Sticking Mechanisms and a Simple Wellsite Test of Monitoring and Optimizing Drilling Mud Properties". SPE 64114-PA. *SPE Drilling & Completion,* **15** (2): 97-104.

Where M_0 is the torque which is required to free the ball, d_b is the diameter of the ball, β is the mudcake thickness per unit square root of time, τ_0 is the shear stress of the cake, and t is the filtration time.

From the Eq. 3, the stickance value, sign s, is the following if we simplify with the torque and time:

$$s = \frac{2}{3}\pi d_b^{3/2}\beta^{3/2}\tau_0 \qquad \text{(Eq. 4)}$$

The stickance is capable to compare different muds to each other. If we use the same tester equipment, the d_b is the same for all muds. The difference will come from the two other parameters.

The mudcake thickness, β, is most sensitive to the solids content of the mud, typically varies between 0.0004 in/s$^{1/2}$ and 0.003 in/s$^{1/2}$. Temperature also affects β, as temperature increases, the filtrate viscosity decreases, growth of the mudcake accelerate.[1]

The shear stress of the cake, τ_0 is a function of differential pressure, temperature and mud type. The effect of temperature us on the interparticle forces and it is not easy to quantify and it is maybe mud-specific. But it is clear, that the τ_0 is proportional to the differential pressure at low and medium pressures. At very high differential pressures, the mudcake starts to behave more like a rock, and the yield stress will be very high what produces a very large shear stress also. The range of the value of τ_0 is typically between 0.03 Δp and 0.1Δp for low differential pressures. At very high differential pressures, the shear stress will approach 0.35 Δp.

For a summary, we can state the following: filter cake quality is depending on many parameters, but mainly on the filter cake thickness and the shear stress of the cake, while the filter cake thickness is depending on the solids content and the temperature and the shear stress in depending on the temperature and the differential pressure.

3.4 Contact Area

Another factor what has a huge effect on differential sticking is the contact area between the drillstring and the mudcake. The effective contact area could be described as the following for a simple case, where the drillstring has a constant diameter at the permeable formation zone:

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[1] Underhill W. B., Moore L., Meeten G.H. Model-Based Sticking Risk Assessment for Wireline Formation Testing Tools in the U.S. Gulf Coast. Presented at the 1998 SPE Annual Technical Conference and Exhibition, Now Orleans, Louisiana, USA 27-30 September 1998. SPE-48963-MS.

$$A_e = 2L_{ep}\sqrt{\left(\frac{D_h}{2}-h_{mc}\right)^2-\left(\frac{D_h}{2}-h_{mc}\frac{D_h-h_{mc}}{D_h-D_{op}}\right)^2} \qquad \text{(Eq. 5)}$$

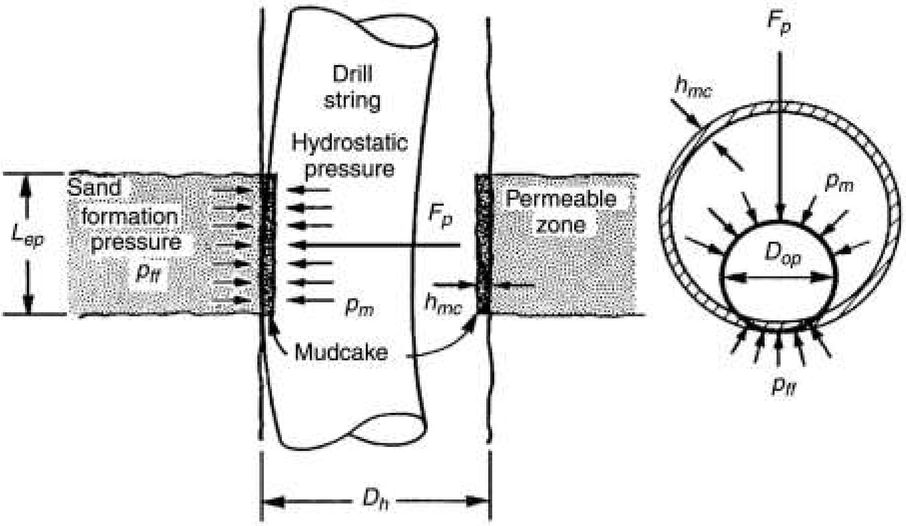

Figure 10: Explanation figure for contact area[1]

Where A_e is the effective contact area, L_{ep} is the length of the permeable formation, D_h is the diameter of the hole, h_{mc} is the thickness of the mudcake and D_{op} is the outside diameter of the drilltstring. As you can see, contact area is influenced by four factors.

It is true that the length of the permeable formation affects the contact area, but in many cases, we have to drill very long sections in high permeability formations, because it could be the goal of the drilling, if it is a hydrocarbon-saturated reservoir, so we can not strive to drill less in this formation. In some cases, the questionable permeable layer is water-containing or a depleted hydrocarbon reservoir, when we could cut the length. In this case, during the planning stage, we have to strive to minimize the drilled section in this layer.

The second factor is the difference between the hole radius and the mudcake thickness. The hole radius is quite fix, it is influenced by both economical and mechanical factors. The other side, the thickness of the mudcake was discussed in the previous subchapter. We could thin the mudcake by keeping the fluid loss, the solids content and the mud temperature as low as it possible.

There is a margin in the third factor, the difference between the hole diameter and the string outside diameter. In the literature authors often refer this as pipe-to-hole diameter ratio.

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[1] PetroWiki. 2015. Differential Sticking. 26 June 2015. http://petrowiki.org/images/a/a3/Devol2_1102final_Page_434_Image_0001.png (accessed 14 September 2015).

There are numerous technique to reduce this ratio, many of them collected by Gibson et al[1] and Dupriest et al[2]. In most cases, the differential sticking occurs at the BHA section of the string, because in this section is the highest the pipe-to-hole diameter ratio.

The above-BHA section could be simplified to the recommendation of using the possible smallest diameter drillpipe.

In BHA design the first step usually to leave the DCs, rather use of HWDPs to maintain the desired WOB. DCs has a slick body, what is critical in terms of contact area, in contrast HWDPs only have a wear pad in addition to joints. In numbers it means that DCs have 30 ft of critical length (entire length) while HWDPs have only 6 ft. In the majority of the cases, HWDPs could replace DCs in high differential potential zones. The buckling resistance could be the bottleneck, but it is turning out in the planning phase. If it not possible to eliminate all DCs, it is recommended to use spiral DCs, which was shown in Figure 4. The spiral lines on the DC wall provide that there is not enough coherent contact area what needed to differentially stuck. In highly deviated and horizontal wells we could take one step further, as we could replace the HWDPs to normal drillpipes. The use of conventional drillpipes with shorter tool joints reduces the contact length with the borehole from about 6 ft with HWDP to less than 3 ft per joint as illustrated in Figure 11. This 3 ft is one tenth of the starting point, the DC's contact area.

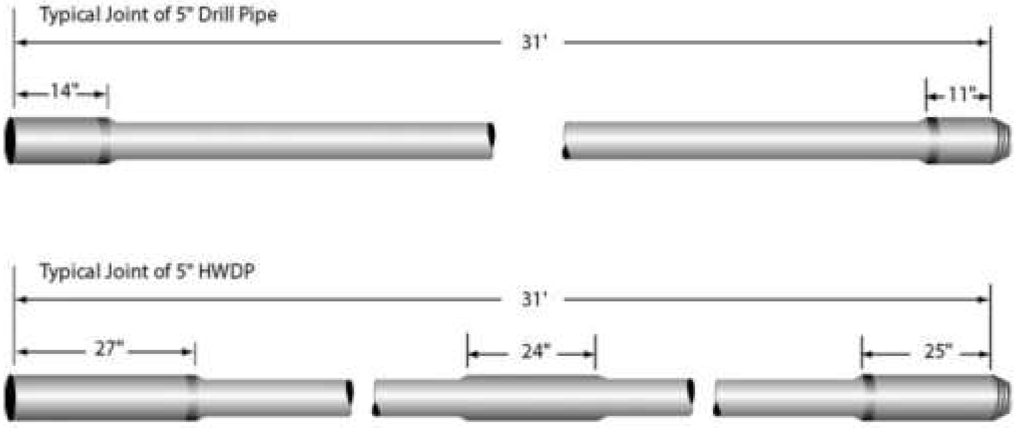

Figure 11: Comparison of possible contact area of HWDP and drillpipe[2]

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[1] Gibson M. T. And Tayler P. J. 1992. Optimal Applications Engineering and Borehole Stability Analysis Avoids Differential Sticking and Leads to Successful Openhole Completion of North Sea Horizontal Well. Presented at the 67th Annual Technical Conference and Exhibition of the SPE, Washington, DC, USA, 4-7 October 1992. SPE-24615-MS.

[2] Dupriest, F. E.; Elks Jr., W. C. and Ottesen, S. 2010. Design Methodology and Operational Practices Eliminate Differential Sticking. Presented at the 2010 IADC/SPE Drilling Conference and Exhibition held in New Orleans, Louisiana, USA, 2–4 February 2010. SPE-128129-MS.

Another option to reduce contact area to stop using slick BHA, rather use fully stabilized BHA, what means that there are stabilizers used and the spacing grants that there is no wall contact.

There is usually one more tool in BHA what has the same risk as a DC, this is the drilling jar. Drilling jar also has a slick body which is undesirable in high risk drilling. The contact area of the jar could be reduced with standoff subs. This standoff sub has a slightly larger OD than the tool's nominal OD and it could reduce wall contact and the resulting wear that occurs during drilling. But it also helps to improve hole cleaning, while decreases torque and drag during directional drilling. An example for standoff subs shown in Figure 12 from Schlumberger. Drilling jar optimization has another point, which is relevant if the sticking has occurred. This is the jar placement to maximize the jar firing power.

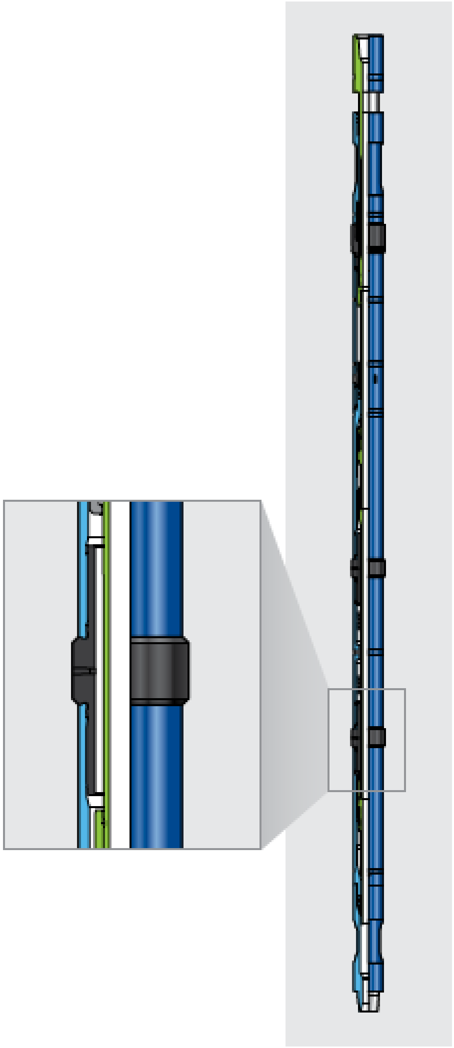

Figure 12: Standoff subs for drilling jar[1]

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[1] Schlumberger. 2012. Standoff Subs. http://www.slb.com/~/media/Files/smith/product_sheets/standoff_sub_ps.pdf (accessed 14 September 2015).

3.5 Other Parameters

There are some other parameters, which not strictly connected with the above ones, but not less important.

3.5.1 Static Time

Static time is one of the necessary condition to differential sticking. From that it makes sense to avoid static time whenever it possible.

The reason behind that is when the pipe becomes stationary, the pressure within the contact area begins to decline immediately, as could be seen in Figure 13. This continues as long as there is sufficient differential pressure between the cake and formation to extract filtrate from the cake. As the fluid pressure declines, the differential force across the pipe is transferred to the solids in the cake. The increase in this stress between solids results in the development of shear strength within the cake and increased contact force between the cake solids and pipe.[1]

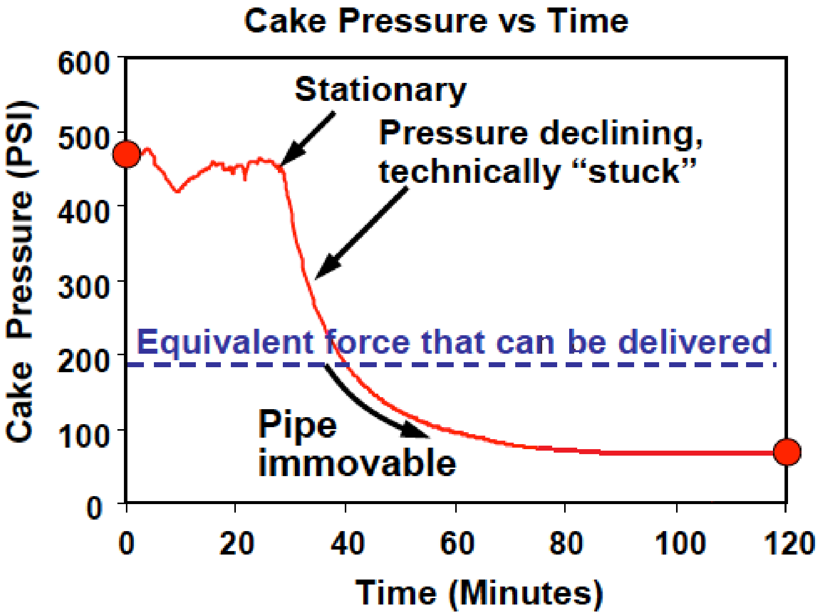

Figure 13: Time dependency of differential sticking[2]

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[1] Outmans H. D. Mechanics of Differential Pressure Sticking of Drill Collars. Presented at the Annual Fall Meeting of Southern California Petroleum Section, Los Angeles, California, USA, 17-18 October 1957. SPE-963-G.

[2] Dupriest, F. E.; Elks Jr., W. C. and Ottesen, S. 2010. Design Methodology and Operational Practices Eliminate Differential Sticking. Presented at the 2010 IADC/SPE Drilling Conference and Exhibition held in New Orleans, Louisiana, USA, 2–4 February 2010. SPE-128129-MS.

As you can see in the Figure, until a critical limit in static time, the shear stress is not great enough to restrain the string against the pull-out, in the Figure, this critical static time is 40 minutes. The value of the critical static time is depending on the mud properties and the differential pressure, but it can not be predicted with the industry's present knowledge. It is a fine approximation, if we say that, until 5 to 10 minutes of static time we are in safe. If the risk of sticking is high, there is a practice to make sure there is enough to for example a connection. The pipe is allowed to sit still for a relatively short and safe period of time and the force required to initiate movement is measured. The still-pipe time is increased progressively to that which is required. If the trend in the pullout force is acceptable, the crew proceeds to make the connection.[2]

An interesting consequence of the relationship between filtrate loss, strength development, and time is that thin cakes may develop shear strength much faster than thick cakes because they may require less time to lose their internal pressure, but the contact area is greater in thick cakes, so if we grant enough static time thick cakes to develop shear strength then it is much harder to free the pipe.

3.5.2 Formation

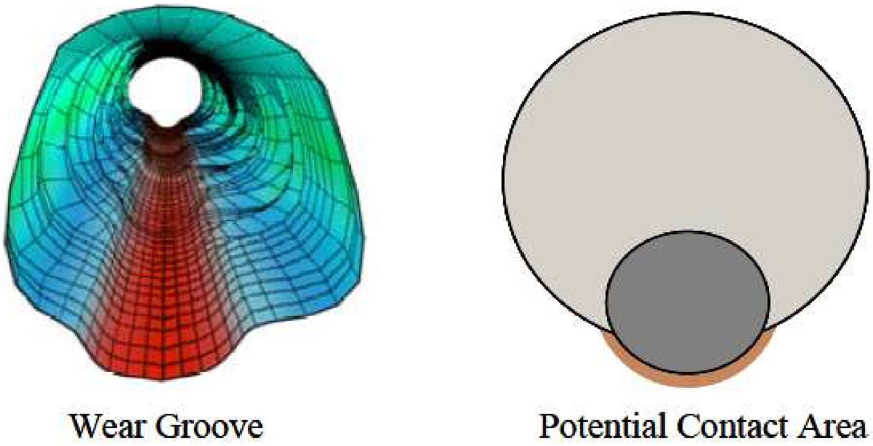
Differential sticking does not have the same risk in every formation. Criterion of differential sticking is a permeable formation, and of course, high differential pressure, what could be easily created in low pore pressure layers. So in view of differential sticking the best formation has low pore pressure, while the permeability is high. The best examples for a formation like this, are the depleted hydrocarbon reservoirs.

We can not really influence the natural specifications of the formations. The best we could do, to get the proper information about formations, and prepare for preventing the differential sticking in the problematic zones. The pore pressure of formation a factor what we absolutely can not influence. The effects of the high permeability could slightly eliminate by proper control of fluid loss, and solid agents in the mud. It was discussed in the subchapter 3.3.

3.5.3 Well Path

The well path, within it the inclination could be a factor in differential sticking. Inclination angles helps the differential pressure to hold the pipe on the borehole wall. Especially dangerous if there is a dogleg in the problematic permeable layer. At high inclination, the string lays down on the bottom wall of the hole. This could be hazard while drilling a relatively low pore pressure reservoir.

There is another problem with high inclination angles, that the rotation of the tool joints or tube body against the bottom of the hole creates a trench on the bottom, called groove. The severity of groove would depend on the rock hardness, normal force, string rotations, and roughness of hardbanding on the tool joints.



Wear Groove

Potential Contact Area

Figure 14: How the wear groove increases contact area[1]

Grooving bears similarities to key seating, but that term refers to a mechanical wedging process in doglegs or ledges. The groove persists for thousands of feet and offers no mechanical resistance that has been noted. However, it creates a significant differential sticking risk because its curvature will be very close to that of the tool joints that created it and the increase in contact area is dramatically, as you can see in Figure 14.

The groove cannot be eliminated but its impact can be minimized. As previously mentioned in chapter 3.4, HWDP could been replaced with conventional drillpipe at intermediate and high angles. One step further, if we take care to use to possible smallest tool joints with the drillpipes.

3.5.4 Hydraulics

According to more papers in the literature it can be stated that the hydraulics, especially the flow pattern could be a significant factor in differential sticking. Early research[2] confirm that turbulent flow pattern could prevent differential sticking, because turbulent flow characteristics minimize the filter cake buildup, consequently the differential sticking would not occur, because a massive filter cake is necessary for sticking.

On the other side, turbulent flow can not manageable every occasion, because turbulent flow has greater chance to leak-off, thereby fluid loss into the formation, which also could cause

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[1] Dupriest, F. E.; Elks Jr., W. C. and Ottesen, S. 2010. Design Methodology and Operational Practices Eliminate Differential Sticking. Presented at the 2010 IADC/SPE Drilling Conference and Exhibition held in New Orleans, Louisiana, USA, 2–4 February 2010. SPE-128129-MS.

[2] Adams N. 1977. A Field Case Study of Differential-pressure Pipe Sticking. Presented at the 52nd Annual Fall Technical Conference and Exhibition of the SPE, Denver, Colorado, USA, 9-12 October 1977. SPE-6716-MS.

differential sticking. As conclusion, it could be stated that it is good to strive to achieve turbulent flow in differential sticking areas, but only if we previously ascertained that it could be managed without fluid loss.

3.6 Summary of influencing parameters

In the Table 1 below, there is a short summary from the chapter of the parameters what could influence the differential sticking, and recommendations how to eliminate the effect of each parameter.

Table 1: Differential sticking parameters and recommendations for each one

Parameter	***Recommendation***	
Differential pressure	Should be low as possible as it can be, by optimal chosen mud weight	*⇓Δp*
Solids control	One constantly running centrifuge on site.	*✓Centrifuge*
Generic mud type	Oil-based mud, but if it cannot feasible polymer water-based mud is also an option	*✓Oil-based mud*
Specific mud formulation	Add lubricant to the mud to reduce sticking potential	*✓Proper lubricant*
Fluid loss	Add blocking solids, which is big enough to control fluid loss in high permeability formations	*✓Proper blocking solids*
Filter cake quality	Keep the following as low as it possible: temperature of the mud, solids content of the mud, differential pressure	*⇓T_{m},* *⇓Solids content,* *⇓Δp*
Length of permeable formation	If it is not a valuable reservoir try to minimize the length	*⇓L_{ep}*
Pipe-to-hole diameter ratio	Should be keep as low as possible by eliminate DCs, even HWDPs and strive to use drillpipes with the smallest OD	*⇓# of DCs and HWDPs*

BHA design	Avoid slick BHA, use fully stabilized BHA	*✗ Slick BHA* *✓ Stabilized BHA*
Drilling jar	Use standoff subs	*✓ Standoff subs*
Static time	Keep as low as possible, never exceed 10 minutes	⇓ t_s
Well Survey	Avoid doglegs in high permeable zones, use drillpipes instead of HWDPs in horizontal and high inclination wells	*✗ Doglegs in permeable layers* *⇓# of HWDPs in horizontal wells*
Hydraulics	If there is no danger to fluid loss with turbulent flow, try to manage turbulent flow to reduce filter cake buildup	*✓ Turbulent flow pattern*

4 Neural Network Modeling

This chapter is a short overview about neural network modeling, what is it, how is it developed, and why was it chosen for prediction.

4.1 General Information

A neural network is a powerful computational data model that is able to capture and represent complex input-output relationships. The motivation for the development of neural network technology stemmed from the desire to develop an artificial system that could perform "intelligent" tasks similar to those performed by the human brain. Neural networks resemble the human brain in the following two ways:

- A neural network acquires knowledge through learning.
- A neural network's knowledge is stored within inter-neuron connection strengths known as synaptic weights.

The true power and advantage of neural networks lies in their ability to represent both linear and non-linear relationships and in their ability to learn these relationships directly from the data being modeled. Traditional linear models are simply inadequate when it comes to modeling data that contains non-linear characteristics.[1]

The simplest definition of a neural network is provided by the inventor of one of the first neurocomputers, Dr. Robert Hecht-Nielsen. With his words:

> "...a computing system made up of a number of simple, highly interconnected processing elements, which process information by their dynamic state response to external inputs."[2]

The basic structure of neural network is a computer representation of a biological neuron (nerve cell) that is interconnected with other neurons (a brain). Mathematically, neural network can be interpreted as a multi-variable non-linear regression. It initially assumes a random relationship between all inputs and the desired outputs. By comparing its first attempt at an answer to the desired output, it self-modifies this initial random relationship into a relationship that best fits the outputs. The network is presented with many example of

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[1] Neurosolutions.com. 2015. What are Neural Networks & Predictive Data Analytics? http://www.neurosolutions.com/products/ns/whatisNN.html (accessed 15 September 2015).

[2] Caudill M. 1989. *Neural Network Primer: Part I.* AI Expert

inputs and outputs, and relationships are learned after reviewing the examples over and over again.[1]

The main advantages of neural network over traditional methods:[2]

- Does not require a mathematical model to describe the predictive relationship
- Yields robust solutions with only a few training examples
- Preserves original data variability in the neural network constructed mathematical model
- Will not over-predict mean values
- Interactive and allows the operator to use his experience and knowledge to train the network

Neural network modeling is used for tasks what demand huge computational performance but also rely on difficult relationships, which are usually need human decide. The most typical task, such as:

- Stock market prediction
- Weather prediction
- Employee selection and hiring
- Electrical load forecasting
- Medical diagnosis
- Fingerprint recognition
- Oil reserves estimation
- Permeability estimation
- Production forecasting
- Hydraulic fracturing forecast
- Stuck pipe prediction

The last five areas, what are underlined, related to petroleum engineering, which prove that neural network modeling is a widely useable tool in oil and gas industry.

4.2 Historical Overview

The first neural network models go back to the 1940s. In 1943, Warren S. McCulloch, a neuroscientist, and Walter Pitts, a logician, developed the first conceptual model of an artificial neural network. In their paper, they describe the concept of a neuron, a single cell

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[1] Murillo A., Neumann J., Samuel R. Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling. 2009. Presented at the 2009 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA 4-8 April 2009. SPE-120128-MS.

[2] Petroleum Software Technologies. 2008. *Neural Network Lap User's Guide.*

living in a network of cells that receives inputs, processes those inputs, and generates an output.[1]

Although their work was breakthrough, it had errors and limitations. In further development, Rosenblatt played a pivotal role, who proposed the “perceptron” in 1957. Perceptron is an algorithm for supervised learning of binary classifiers; functions that can decide whether an input belong to one class or not.[2]

The next milestone in development was the introduction of backpropagation algorithm. It was invented by Rumelhart and McClelland in 1986. Backpropagation is an abbreviation for "backward propagation of errors", it is a common method of training artificial neural networks used in conjunction with an optimization method such as gradient descent. The method calculates the gradient of a loss function with respect to all the weights in the network. The gradient is fed to the optimization method which in turn uses it to update the weights, in an attempt to minimize the loss function.[3]

The first application of neural network in stuck pipe prediction was in 2006.[4] Before that, there were attempts to predict stuck pipe events, by using multivariate statistical analysis. But with using neural network, todays there are excellent results in stuck pipe prevention, if it was applied during the planning phase.[5]

4.3 Working Method of Neural Network Modeling

Natural neurons receive signals through synapses located on the dendrites or membrane of the neuron. When the signals received are strong enough the neuron is activated and emits a signal though the axon. (Figure 15) This signal might be sent to another synapse, and might activate other neurons. The complexity of real neurons is highly abstracted when modeling neurons.

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[1] Shiffman D. (2012) “The Nature of Code”. first edition. ISBN 0985930802.

[2] Freund, Y.; Schapire, R. E. (1999). "Large margin classification using the perceptron algorithm". Machine Learning 37 (3): 277–296.

[3] Rumelhart, D. and J. McClelland (1986). “Parallel Distributed Processing”. MIT Press, Cambridge, Massachusetts, USA.

[4] Siruvuri, C., Nagarakanti, S., Samuel, R.: Stuck Pipe Prediction and Avoidance: A Convolutional Neural Network Approach. 2006. Presented at the 2006 IADC/SPE Drilling Conference, Miami, Florida, USA, 21 February 2006. SPE 98378-MS.

[5] Murillo A., Neumann J., Samuel R. Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling. 2009. Presented at the 2009 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA 4-8 April 2009. SPE-120128-MS.

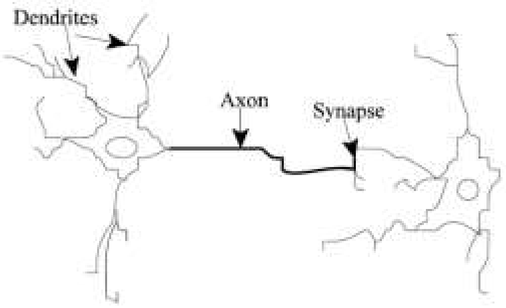

Figure 15: Schematic diagram of a natural neuron[1,]

These basically consist of inputs (like synapses), which are multiplied by weights (strength of the respective signals), and then computed by a mathematical function which determines the activation of the neuron. Another function (which may be the identity) computes the output of the neuron. Neural networks combine neurons in order to process information.[1] There is a guide to the terminologies in Table 2.

Table 2: Terminology of Neurons[2]

Biological Terminology	**Artificial Neuron Terminology**
Neuron	Node/Unit/Cell/Neurode
Synapse	Connection/Edge/Link
Synaptic Efficiency	Connection Strength/Weight
Firing Frequency	Node Output

When creating a functional model of the biological neuron, there are three basic components of importance. First, the synapses of the neuron are modeled as weights. The strength of the connection between an input and a neuron is noted by the value of the weight. Negative weight values reflect inhibitory connections, while positive values designate excitatory connections. The next two components model the actual activity within the neuron cell. An adder sums up all the inputs modified by their respective weights. This activity is referred to as linear combination. Finally, an activation function controls the amplitude of the output of

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[1] Gershenson, C. (2001). Artificial Neural Networks for Beginners. Formal Computational Skills Teaching Package, COGS, University of Sussex.

[2] Dongare A. D., Kharde R. R., Kachare A. D. 2012. Introduction to Artificial Neural Network. *International Journal of Engineering and Innovative Technology* **2** (1): 189-194. ISSN:2277-3754

the neuron. An acceptable range of output is usually between 0 and 1, or -1 and 1. This could be seen in the Figure 16.

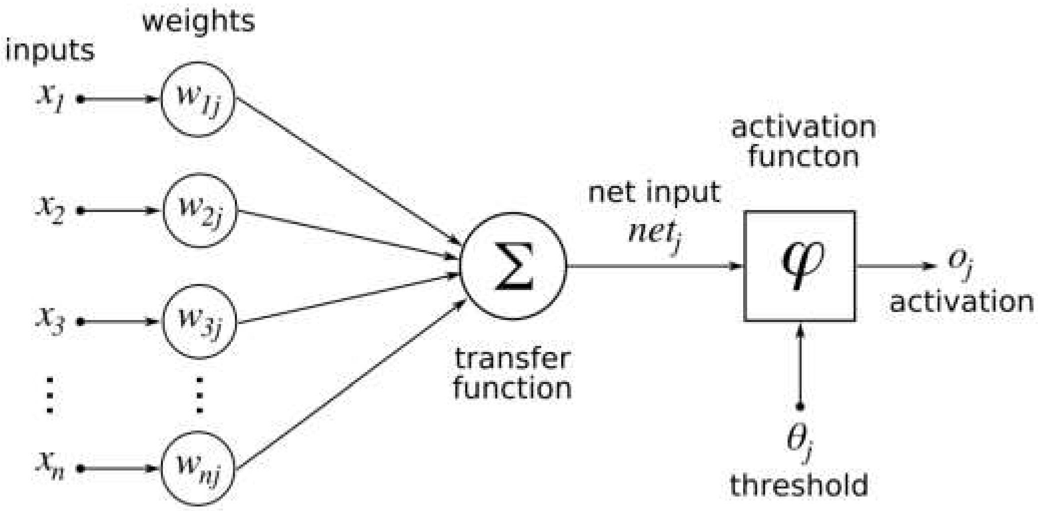

Figure 16: Schematic diagram of an artificial neuron[1]

From this model the interval activity of the neuron, *net*$_j$, is the following:

$$net_j = \sum_{j=1}^{n} w_j x_j \quad \text{(Eq.) 6}$$

The output of the neuron, o_j, would therefore be the outcome of some activation function on the value of *net*$_j$.

It is reasonable to presume that neurons in an animal's brain are "hard wired".[2] It is also obvious that animals, especially the higher order animals, learn as they grow. In artificial neural networks, learning refers to the method of modifying the weights of connections between the nodes of a specified network. Learning is the process by which the random-valued parameters of a neural network are adapted through a continuous process of simulation by the environment in which network is embedded.

Learning may be categorized as supervised learning, unsupervised learning and reinforced learning. In supervised learning, a teacher is available to indicate whether a system is performing correctly. This is in contrast with unsupervised learning, where no teacher is available and learning must rely on gathered data obtained by the system examining different sample data. Reinforced learning is the mixture of the above two types.

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[1] Andrewjamesturner.co.uk. 2015. Artificial Neural Networks. http://andrewjamesturner.co.uk/ArtificialNeuralNetworks.php (accessed 15 September 2015).

[2] Dongare A. D., Kharde R. R., Kachare A. D. 2012. Introduction to Artificial Neural Network. *International Journal of Engineering and Innovative Technology* **2** (1): 189-194. ISSN:2277-3754

The next step to develop is the backpropagation. This could be used if the neurons are organized in layers. In this case neurons send their signals “forward”, and then the errors are propagated backwards. The network receives inputs by neurons in the input layer, and the output of the network is given by the neurons on an output layer. There may be one or more intermediate hidden layers. The backpropagation algorithm uses supervised learning, which means that we provide the algorithm with examples of the inputs and outputs we want the network to compute, and then the error (difference between actual and expected results) is calculated. The idea of the backpropagation algorithm is to reduce this error, until the network learns the training data.[1]

Backpropagation became more important when the limitations of other network turned out. The backpropagation network is a multi-layer network that contains at least one hidden layer and of course an input and an output layers. The number of the layers is depending on the number of the inputs and outputs, as well as the nature of the problem.

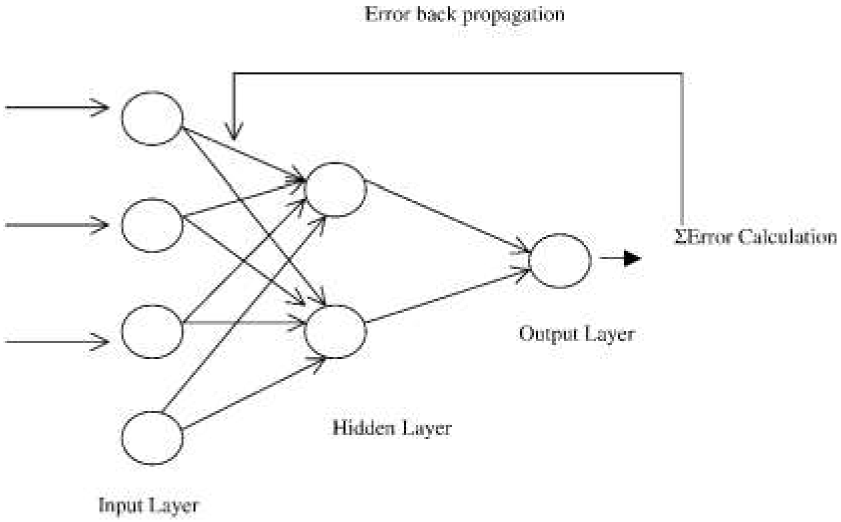

Figure 17: Layers structure of backpropagation network

Execution of back propagation model made up from two phases. First phase is the training phase while the second phase is called testing phase. Training, in back propagation is based on a rule that tends to adjust weights and reduce system error in the network. Input layer has neurons equal in number to that of the inputs. Of course in the other side, output layer neurons are same in the number as number of outputs. Number of hidden layer neurons is decided by trial and error method using the experimental data.[2]

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[1] Gershenson, C. (2001). Artificial Neural Networks for Beginners. Formal Computational Skills Teaching Package, COGS, University of Sussex.

[2] Dongare A. D., Kharde R. R., Kachare A. D. 2012. Introduction to Artificial Neural Network. *International Journal of Engineering and Innovative Technology* **2** (1): 189-194. ISSN:2277-3754

4.4 Applications in Stuck Pipe Prediction

Because stuck pipe problems are one of the most expensive drilling problems, there is an intention from the industry to prevent it. For prevention, it is necessary to know in advance if there is a possible sticking situation. To satisfy this demand, drilling engineers experimented to make a prediction tool for sticking, based on different statistical models.

First models in industry based on multivariate statistical analysis. One of these, maybe the most cited is by Biegler and Kuhn[1] It was introduced in 1994. Multivariate statistical analysis could reach good prediction percentage in well-known fields, but have limitations in unknown areas.

Neural network modeling for stuck pipe prediction firstly appeared in the paper of Siruvuri et al[2]. The authors used a convolutional type neural network in their work, and the model was able to predict with the error within 5%. One of most important conclusion of the paper is that the success of the prediction depends mainly on the properly chosen parameters and the quality of the database.

Other researches[3,4,5] are the proof of that the neural network modeling is an applicable tool for stuck pipe prediction. These papers use different type of neural network modeling in different type of fields, but the result is the same: with a well-prepared neural network model could predict the pipe sticking events with very good percentage. Murillo et at[5] besides that, compared neural network modeling with an other computational tool, the fuzzy logic method. They had the result that the neural network modeling has better prediction efficiency than fuzzy logic.

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[1] Biegler M. W. Kuhn G. R. Advances in Prediction of Stuck Pipe Using Multivariate Statistical Analysis. 1994. Presented at the IADC/SPE Drilling Conference, Dallas, Texas, USA, 15-18 February 1994. SPE-27529-MS.

[2] Siruvuri C., Nagarakanti S., Samuel R. Stuck Pipe Prediction and Avoidance: A Convolutional Neural Network Approach. 2006. Presented at the IADC/SPE Conference, Miami, Florida, USA, 21-23 February 2006. SPE-98378-MS.

[33] Miri R., Sampaio J., Afshar M., Lourenco A. Development of Artificial Neural Networks To Predict Differential Pipe Sticking in Iranian Offshore Oil Fileds. 2007. Presented at the 2007 International Oil Conference and Exhibition, Veracruz, Mexico, 27-30 June 2007. SPE-108500-MS.

[4] Al-Baiyat I., Heinze L. Implementing Artificial Neural Networks and Support Vector Machines in Stuck Pipe Prediction. 2012. Presented at the SPE Kuwait International Petroleum Conference and Exhibition, Kuwait City, Kuwait, 10-12 December 2012. SPE-163370-MS.

[5] Murillo A., Neumann J., Samuel R. Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling. 2009. Presented at the 2009 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA 4-8 April 2009. SPE-120128-MS.

The author of this thesis thought that, if the neural network modeling could predict sticking, it would be able to helps in the analysis sticking events, in the following way:

1. Neural network trained on the available data, the database included both sticking and non-sticking data lines.
2. Analysis the sticking situations, and came up with solution to avoid the sticking situations.
3. Modify the data lines of the original sticking situations according to the analysis.
4. Run the prediction with neural network model for the new situations.

If the model predicts the new situation as non-sticking, the applied modifications are enough to prevent sticking. If the prediction is still sticking, other actions necessary to prevent sticking. When all three cases predicted as non-sticking, the connection, if there is any, could be located.

5 Information of Wells and Description of Sticking Situations

In this chapter, the author would like to give an overview about the wells, the general information, environmental data. Later on, the stuck situation and the antecedent of these for each well were described.

5.1 General Information of the Wells

This subchapter contains the general information about the wells, well paths and well sections.

5.1.1 TUS-80

The TUS-80 well was the firstly drilled well of the investigated three wells. It was drilled in Serbia, in Vojvodina region between 21.04.2013 and 15.05.2013. The aim of the drilling was to explore the possibilities of a deeper reservoir layer below the known Endrőd formation. In Table 3 and Table 4 there is a summary of the main information about the well.

Table 3: General well information of TUS-80

Event	Description
Country	Serbia
State	Vojvodina
Field	Turija
Well	TUS-80
Wells Class	Exploratory
Well Type	Directional
Coordinates	45°32'47.33" N 19°50'8.70" E

This is the most problematic well in terms of view of data quantity and quality. The available data form this well is drilling daily reports, directional data, mud reports, depth- and time based logs. Unfortunately, the logs are only available in picture format, what the author had to convert into numerical data by the author. This procedure described in Appendix A.

Table 4: Drilling activity information of TUS-80

Event	Description
Spud date	21.04.2013
End date	15.05.2013
Final depth (MD)	2330 m
Final depth (TVD)	2259 m
Rotary table	5.2 m
Operator	TDE Field Services
Drilling rig	DM-7000

The location of the well is in the middle of Vojvodina, which is an autonomous province within Serbia, surrounded by the Hungarian, Croatian, and the Romanian border. The accessibility of the well is good; it could be accessible in public roads. The exact location could be seen in the Figure 18, and the distances from nearby bigger cities is in the Table 5.

Table 5: Distance of TUS-80 well form important cities

Place	Distance
Novi Sad (capital of Vojvodina)	30 km
Belgrade (capital of Serbia)	95 km
Subotica	64 km
Kikinda	58 km

Figure 18: Position of TUS-80 well in physical map of Serbia[1]

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[1] ezilon-com 2009. http://www.ezilon.com/maps/images/europe/physical-map-of-Serbia.gif (accessed 19 September 2015).

The structure of the well is quite easy, there is one conductor casing section, one surface and one production casing section. Detailed information can be found in Table 6.

Table 6: Well sections for TUS-80

Well Section	Bit size (in)	Casing OD (in)	MD (m)	TVD (m)	Mud type	EMW (spec. gravity)
I	-	13 3/8	30	30	-	-
II	12 ¼	9 5/8	1161	1161	Gypsum-poly	1.15
III	8 ½	7	2326	2255.2	Gypsum-poly	1.15

The well is deviated, the schematic well path could be seen in Figure 19. The KOP is at 1370m, the maximum horizontal departure is 346.84m, and the maximum dogleg is 5.65$^{\circ/30m}$.

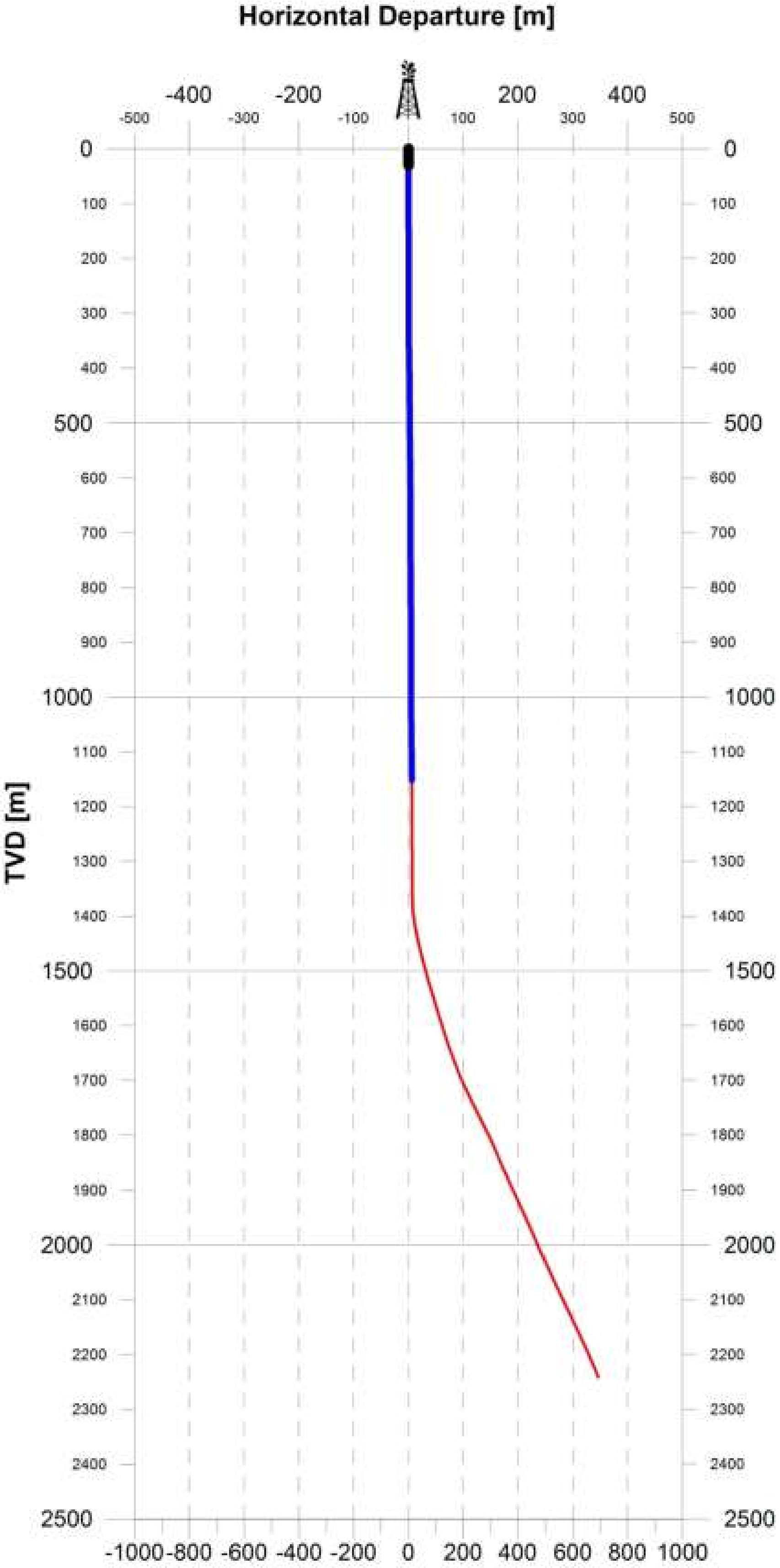

Figure 19: Schematic well path of TUS-80

5.1.2 Mk-X3 St-1

Nafta Industrija Serbija JSC (NIS Gazprom Neft) contracted TDE Field Services to design and manage the drilling of the Mk-X3 development directional well. The drilling started on 06.04.2014 and reached the projected 2044 m (MD) on 15.04.2014. The reservoir proved poor after evaluation and a sidetrack was to be performed from 750m (MD). The sidetrack was drilled between 23.04.2014. and 06.05.2014.

Table 7: General well information of Mk-X3 St-1

Event	Description
Country	Serbia
State	Vojvodina
Field	Mokrin
Well	Mk-X3 St-1
Wells Class	Development, expected oil produce
Well Type	Deviated sidetrack
Coordinates	45°56'22.98" N 20°26'41.86" E

The quality of the got data is satisfying. The available data are drilling daily reports, mud daily reports, geological daily reports, end report over and above depth- and time-based logs as well as time-based drilling data in numerical form.

Table 8: Drilling activity information of MK-X3 St-1

Event	Description
Spud date	06.04.2014
End date	06.05.2014
Final depth (MD)	2579 m
Final depth (TVD)	2030 m
Rotary table	5.2 m
Operator	TDE Field Services
Drilling rig	MR-8000

The well site is located in Serbia, Vojvodina state. The exact location shown in Figure 20. The drilling point is directly next to the Romanian border. It is accessible from public roads.

Table 9: Distance of Mk-X3 well form important cities

Place	Distance
Novi Sad (capital of Vojvodina)	90 km
Belgrade (capital of Serbia)	127 km
Subotica	63 km
Kikinda	12 km

Figure 20: Position of Mk-X3 well in physical map of Serbia[1]

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[1] ezilon-com 2009. http://www.ezilon.com/maps/images/europe/physical-map-of-Serbia.gif (accessed 19 September 2015).

The well structure is, like the previously showed TUS-80, made up from three sections. One conductor, one surface and one production casing section. Detailed information can be found in Table 10.

Table 10: Well sections for Mk-X3 St-1

Well Section	Bit size (in)	Casing OD (in)	MD (m)	TVD (m)	Mud type	EMW (spec. gravity)
I	-	14	36	36	-	-
II	12 ¼	9 5/8	702	701.98	Gypsum-poly	1.10
III	8 ½	5 ½	2579	2029.9	Gypsum-poly	1.13

The well is deviated, the sidetrack is from 750m and the formation was found in 100% around 771 m (MD). The well was built up to 48°, the maximum horizontal departure is 1264.73 m and the maximum dogleg is 6.79$^{°/30m}$.

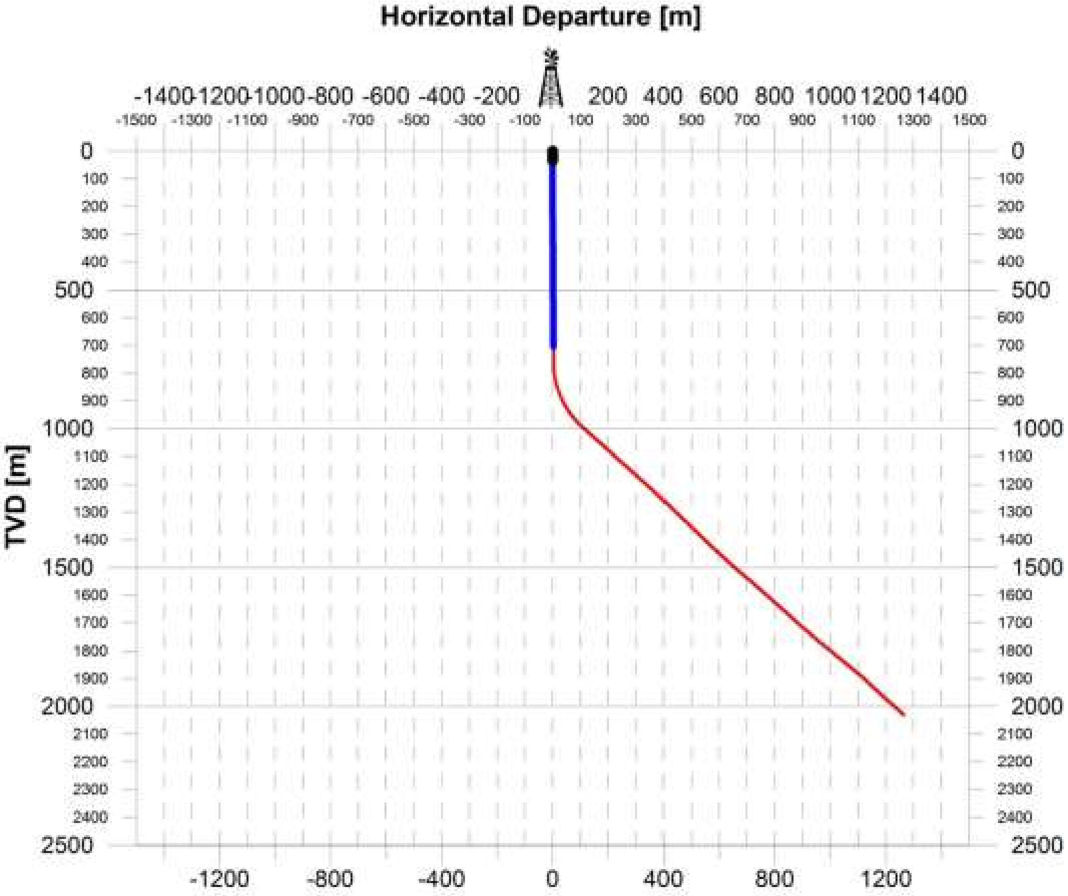

Figure 21: Schematic well path of Mk-X3 St-1

5.1.3 Ve-220

The Ve-220 well is, like the previous two wells, drilled in Serbia, Vojvodina state by TDE Field Services. The goal of the drilling to drill a development well with expected oil production from the Békés formation. The well is drilled between 27.06.2014 and 04.07.2014.

Table 11: General well information of Ve-220

Event	Description
Country	Serbia
State	Vojvodina
Field	Velebit
Well	Ve-220
Wells Class	Development, expected oil produce
Well Type	Deviated
Coordinates	45°58'52.05" N 19°55'41.47" E

Like the previous well, Mk-X3 St-1, the quality of the got data is satisfying. The data collection made up of drilling daily reports, mud daily reports, geological daily reports, end report over and above depth- and time-based logs as well as time-based drilling data in numerical form.

Table 12: Drilling activity information of Ve-220

Event	Description
Spud date	27.06.2014
End date	04.07.2014
Final depth (MD)	1177 m
Final depth (TVD)	800 m
Rotary table	5.2 m
Operator	TDE Field Services
Drilling rig	MR-8000

The well site is located in Serbia, Vojvodina state, around 40 km far from Mk-X3 well. The exact location shown in Figure 22. It is accessible from public roads.

Table 13: Distance of Ve-220 well form important cities

Place	Distance
Novi Sad (capital of Vojvodina)	72 km
Belgrade (capital of Serbia)	132 km
Subotica	24 km
Kikinda	45 km

Figure 22: Position of Ve-220 well in physical map of Serbia[1]

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[1] ezilon-com 2009. http://www.ezilon.com/maps/images/europe/physical-map-of-Serbia.gif (accessed 19 September 2015).

The well structure is like the previous ones made up from three sections. One conductor, one surface and one production casing section. The production section was not cased due to the sticking problem which is shown in the next subchapter. Detailed information from the well sections can be found in Table 14.

Table 14: Well sections for Ve-220

Well Section	Bit size (in)	Casing OD (in)	MD (m)	TVD (m)	Mud type	EMW (spec. gravity)
I	-	14	35	35	-	-
II	12 ¼	9 5/8	245	245	Gypsum-poly	1.06
III	8 ½	-	1177	800	Gypsum-poly	1.10

The well trajectory is slightly different from the previous two, because in this well the horizontal department is quite big compared to maximum TVD. KOP is at 270m, the well was built up to 65° and the maximum dogleg is 7.27 $^{\circ/30m}$.

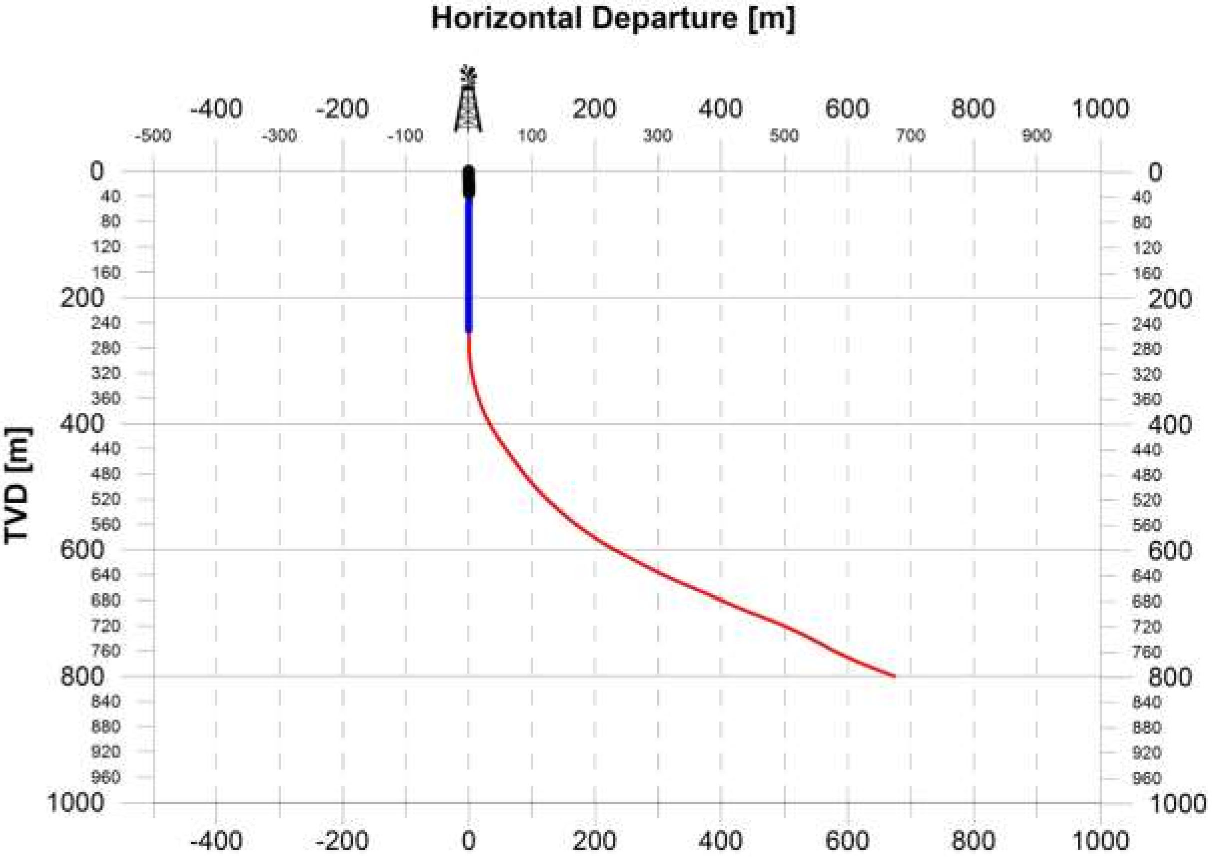

Figure 23: Schematic well path of Ve-220

5.2 Drilling History of the Wells

This subchapter is a description of the concrete differential sticking situations.

5.2.1 TUS-80

The well was drilled without any stuck pipe or well control problem to slightly below the projected 2245 m (TVD), until 2259 m in vertical depth, which means 2330 m measured depth. The differential sticking situation came when they RIH for wiper trip after a one-day long logging session. The drillstring stuck at 2169 m MD, at the BHA section. It took approximately one day to free the pipe.

5.2.1.1 Antecedent of Sticking

Drilling until 2122 m was trouble-free. That day (05.05.2013.) 4 ton Intasol ($CaCO_3$) was added to the mud to prevent fluid losses, because the expected formation was breccia with limestone and metamorphic metaclaystone main grains and there was possibility to fluid loss with the used mud to this formation. Nevertheless, fluid loss to the formation started at 2122 m with 3 m^3/h rate. To control this situation, the following immediate actions were made: stopped the centrifuge to save cuttings in mud, decreased flow rate to 1500 l/min, and slowly added further Intasol and increased adding water from 0.6 m^3 to 2.4 m^3. The total losses this time was 1.8 m^3.

By drilling ahead, the losses decreased to 0 m^3/h, but from 2190m the loss started again with the rate of 2.2 m^3/h. The only action was take to slowly add Intasol and monitoring the losses while drilling. Consequently, the losses increased to 3.5-4 m^3/h from 2220m and increased further to 5 m^3/h from 2240. From 2220 to formation had changed to a clearly metamorphic rock (mainly quartz). At this point adding water and treating mud as per mud program to maintain active pit volume. Decreased drilling parameters used to avoid further losses. As result, from 2300m the losses decreased to 2-3 m^3/h. After reaching the projected TVD, a LCM pill spotted on bottom. It was a 22 m^3 pill mixed with 150 kg/m^3 $CaCO_3$.

The total loss to the breccia formation was 9 m^3 and 68 m^3 to the metamorphic rock.

Table 15: Mud properties in TUS-80 at drilling of the problematic zone

Property	@ 2122m	@ 2178m	@ 2220m	@ 2302m	@ 2330m
Mud Weight (kg/dm^3)	1.15	1.15	1.15	1.16	1.15
Plastic Viscosity (mPas)	22	21	24	23	21
Yield Point (Pa)	24	24	23	21	23
Funnel Viscosity (s)	58	57	59	63	58
API Filtration (ml/30')	4.8	4.9	4.4	4.2	4.4
Cake thickness (mm)	0.5	0.5	0.5	0.5	0.5
Calcium Filtrate (mg/l)	1440	1280	1480	1480	1480
pH	10.0	10.3	9.9	10.3	10.2

After drilling the projected TVD, they performed a wiper trip. During POOH 3 m^3 losses registered. Caustic soda was added (50 kg) to increase alkalinity. During RIH and circulation no formation losses was registered. However, they decided to pump 10 m^3 LCM pill to the bottom. Then POOH for logging, while no losses observed.

5.2.1.2 Sticking Situation

The logging took one day from 1:30 on 08.05.2013 to 1:45 on 09.05.2013. The started to RIH for wiper trip at 2:45. When making a connection at 9:59, the pipe got stuck at 2169m, and the drillstring was lost its movability.

The next approximately one day from 10:00 09.05.2013 to 6:45 10.05.2013 spent to free the drillstring. The following actions were made:

Table 16: Operations summary on 09-10.05.2013 to free the stuck pipe (TUS-80)

From	To	Operation
10:00	10:45	Circulate and reciprocate drillstring because of stuck pipe @ 2169 m with 20 ton, added 1% lubricant to mud
10:45	11:00	Pump high viscosity pill to the well
11:00	13:00	Reciprocate drillstring and circulate with 1600 l/min (2169-70 m)
13:00	14:00	Circulate meanwhile check for free point calculation
14:00	15:45	Circulate with 600 l/min (2169-70 m)and reciprocate drillstring
15:45	19:00	Reciprocate drillstring and circulate 1400 l/min (2169-70 m), while prepare 10 m^3 diesel plug
19:15	20:00	Pump 10 m^3 diesel plug, displace 2m^3 in the annulus, put +10 tons tension on the drillstring
20:00	21:00	Waiting for effect, 1 h, reciprocate string
21:00	22:00	Displace +2 m^3 (4 m^3 total) diesel plug in annulus, waiting 1 h to effect, put + 10 tons on the string
22:00	23:00	Displace +2 m^3 (6 m^3 total) diesel plug in annulus, waiting 1 h to effect, put +10 tons on the string
23:00	00:00	Displace +2 m^3 (8 m^3 total) diesel plug in annulus, waiting 1 h to effect, put +20 tons on the string
00:00	01:00	Displace+2 m^3 (10 m^3 total) diesel plug in annulus, waiting 1 h to effect, put +30 tons on the string
01:00	03:00	Waiting 2 h with string weight on hook
03:00	05:00	Waiting 2 h with string weight + 10 tons on hook
05:00	06:15	Waiting 1,25 h with string weight + 20 tons on hook
06:15	*06:45*	Jar started to work, free drill string

After freeing the pipe backreaming was performed to 2000m, then new BHA was assembled. In the next RIH, from 1909 to TVD there was reaming. From that point, everything went in program.

5.2.2 Mk-X3 St-1

The drilling of the Mk-X3 well was trouble-free, but after evaluation the reservoir graded to poor, and the company decided to sidetrack the well from 850m. The drilling of the sidetrack, named Mk-X3 St-1, was also trouble-free, but after reaching the projected TVD at 2030m, during the PCL logging, the tool was stucked at 2578 m MD at the bottom of the well. It took approximately half a day to free the tool.

5.2.2.1 Antecedent of Sticking

The sidetrack is from 750 m by drilling in sliding mode with a diameter of 8 ½”. Drilling was according to plan until 1852m they had to change the bit. After RIH hole with the new bit, from 1997 m less cutting volume and high torque was observed. Hi-Vis plug had no effect, so drilling parameters decreased. This has also no effect, so decision was made to decrease the number of the DC from 8 to 2 in the string.

Below 1852m, they had to pump 5 m^3 Hi-Vis pill 5 times, because of hole sweeping. The formation below 2000m was mainly clay marl with sandstone streaks and layers, somewhere with coal streaks. At the bottom of the well, at 2579m MD, there were two pills pumped down, one after reaching the projected TVD, and one after a short trip. There were only gas traces in the well, producible quantity not. After the short trip, POOH for logging.

During the drilling of the last section from 2090m to 2579m two centrifuges ran constantly to control solids content of the mud.

Table 17: Mud properties in Mk-X3 St-1 at drilling of the problematic zone

Property	@ 2090m	@ 2226m	@ 2294m	@ 2470m	@ 2545m	@2579m
Mud Weight (kg/dm^3)	1.10	1.11	1.12	1.12	1.12	1.13
Plastic Viscosity (mPas)	18	19	20	18	18	18
Yield Point (Pa)	18	17	18	17	15	17
Funnel Viscosity (s)	56	55	57	54	54	54
API Filtration (ml/30')	3.8	3.8	4.0	3.8	3.8	3.8
Cake thickness (mm)	0.5	0.5	0.5	0.5	0.5	0.5
Calcium Filtrate (mg/l)	1520	1480	1520	1520	1480	1480
pH	9.6	9.7	9.8	9.6	9.7	9.8

5.2.2.2 Sticking Situation

After reaching the projected TVD of 2030m at 2579 m measured depth, they performed a PCL logging. After a logging session at the bottom of the hole, a one-hour logging the tool was stucked at 2578m.

The sticking occurred at 21:00 on 02.05.2014 and the movability was regained at 7:15 on 03.05.2014. The following action were made to free the string:

Table 18: Operations summary on 02-03.05.2014 to free the stuck pipe (Mk-X3 St-1)

From	To	Operation
21:00	00:00	Circulate and reciprocate drillstring because of stuck pipe @ 2578 m meanwhile mixing of 8 m^3 of diesel plug
00:00	03:45	Circulate and reciprocate drillstring because of stuck pipe @ 2578 m meanwhile mixing of 8 m^3 of diesel plug
03:45	04:15	Pump 8 m^3 of diesel plug and displace in the annulus, run all solids control equipment to decrease mud weight from 1.13 to 1.10 spec. grav. As per company man requested.
04:15	05:15	Waiting for effect 1 hour, reciprocate string
05:15	06:15	Displace 8 m^3 of mud in the annulus, waiting for effect 1 hour, reciprocate string
06:15	*07:15*	Attempt to work string free, success, recovered diesel plug

5.2.3 Ve-220

The well Ve-220 is slightly different from the previous two, because it is relatively shallow, the projected TVD was only 800m compared to the 2000+m ones. Further, to this 800m TVD, it has a 670m horizontal departure. After reaching the desired TVD, there were loss circulation problems combined with well control and differential sticking situations. The string stucked in the well two times, at first the string could be freed in short time, but the second time they could not free the string, so the situation ended with the cutting of the drillpipe.

5.2.3.1 Antecedent of Sticking

The drilling of the well began in 27.06.2014. with the 12 ¼” section to 250m. This depth was reached that day, casing setting and cementing was done in the following day. For the next section, mud weight was decreased by .02 s.g. from 1.09 to 1.07. Plus Pollcell SL and $CaCO_3$ was added to reduce fluid losses, and lubricant concentration increased to 3%.

At 1077m MD they had to perform BOP drill, because of formation gas. After that, mud weight raised again to 1.09 s.g., as well additional fluid loss material and NaOH was added to the mud. When POOH, from 775m MD static losses was observed, so overall 11 m^3 LCM pill was pumped down in two rounds. After reaching 800m TVD, lubricant concentration was raised to 4.5%.

Table 19: Mud properties in Ve-220 at drilling of the problematic zone

Property	@ 714m	@ 860m	@ 931m	@ 1095m	@ 1169m	@ 1177m
Mud Weight (kg/dm^3)	1.07	1.07	1.08	1.09	1.09	1.09
Plastic Viscosity (mPas)	19	17	17	15	19	18
Yield Point (Pa)	20	16	12	14	15	14
Funnel Viscosity (s)	51	46	45	45	49	49
API Filtration (ml/30')	4.2	4.2	4.2	4.5	4.4	4.5
Cake thickness (mm)	0.5	0.5	0.5	0.5	0.5	0.5
Calcium Filtrate (mg/l)	1560	1680	1680	1600	1600	1630
pH	9.4	9.4	9.6	9.4	9.5	9.9

5.2.3.2 Sticking Situation

After the drilling, they performed a reaming trip to the bottom. Another 4 m^3 LCM plug was placed in the bottom, and they started to POOH. At 872m measured depth (9:15 05.07.2014) they observed a kick and closed the BOP. Started to circulate, but there was no return. When they tried to continue the POOH, they could not, because the string had stucked. This time, with using the drilling jar, the string could be freed.

Then they tried to recover the circulation, but with no success, there were total losses. The planned to keep the annulus full and continue the POOH, but the string stucked again. This time they could not free the string, and there was no circulation also. LCM plugs were pumped down, but could not stop the losses, so decision was made to spot a cement plug. Job was done while the fluid level in annulus kept full with crude oil.

When running free point tool, it turned out, that the stuck point is at 440 m MD. After this, several times were trying to free the string with no success. The final decision was to cut the DP at 350 m MD and spot a cement plug.

6 Sticking Analysis with Neural Network Modeling

This chapter is the main part of this thesis. It contains the analysis of the sticking situations, possible solutions for them, following the knowledge from the previous chapters. Furthermore, in this chapter, the author described the method how he determined the sticking possibilities with using of Palisade's NeuralTools, which is a neural network modeling build-in for Microsoft Excel. NeuralTools capable to train with network data, test on it and make predictions from new data. NeuralTools was used to check, which of the mentioned modifications could help to prevent sticking.

6.1 Structure of the Model

The concept of the neural network modeling approach in sticking analysis was described in Chapter 4.4. In this subchapter there is a short description of the neural network, how it was built and how it looks like.

The available data for this thesis are drilling daily reports, mud daily reports, geological daily reports, end reports over and above depth- and time-based logs as well as time-based drilling data in numerical form. Time-based numerical logs contain 0,2 Hz data, mud reports contain 3 datasets per day and geological reports are depth-based, while trajectory data are also depth-based. The author had to unite these different data into one model.

The neural network model is build up from datasets. Each dataset is represented in one row in the model. The base of a dataset is the time. Basically, drilling data was taken from every 5 minutes, but in the day immediately before and after the sticking from every minutes.

Thus, the drilling data determinate the basic structure of the model. At this point, every dataset has 13 columns (Well name, date, time, MD, TVD, bit size, bit depth, ROP, WOB, hookload, torque, pump pressure, mud flow rate).

Then, the datasets were extended with different parameters, which are described in the following subchapter. Parameters were determinated for each dataset with Excel functions for the depth of the dataset, or were calculated with the described method. At the end, the model had 44 independent variables for each dataset, and one dependent variable, the sticking status. Sticking status could be sticking and non-sticking, and the actual state could be known from the daily reports, where the time of the sticking were reported.

The aim of the following work is to modify some of the 44 variables of the three datasets when the sticking occurred, to provide that the model would predict the dataset as "non-sticking", instead of the original "sticking".

6.2 Parameters for the Model

According to Siruvuri et al.[1], the key of the success in neural network prediction is a good database for the training session. The database is based on different parameters, so choosing the proper parameters is one of the most important actions.

As a starting point, the author of this thesis followed the paper of Murillo et al[2] in term of parameters, and extended it with some other parameters, which are also important in his opinion. Murillo et al[2] made five dimensionless factors out of from 18 different variables. In this thesis, 36 independent numeric and 8 independent category variables were used.

Unfortunately, some of the necessary parameters are not known from the available data. The missing parameters have to be calculated from the available data. This subchapter is a description of the used parameters, and if one was not available from the original data, the calculations also could be found in this subchapter. The original database made up from time-based logs, drilling daily reports, geological reports, mud reports and surveys.

6.2.1 Differential Pressure

To determine the differential pressures, necessary to know the pore pressures, and the hydrostatic pressure of the mud. However, in drilling conditions, the relevant mud pressure is the ECD. From the given data, mud weights available for each depth, but the author had to calculate the ECD, the pore pressure gradients and the differential pressure.

The calculation of differential pressure contains four steps:

1. Calculation of Annular Velocities, differentiate of cased and open holes:

$$v = \frac{24.5\,Q}{D_h^2 - D_{op}^2} \qquad \text{Eq. (7)}$$

where v is the annular velocity (ft/min), Q is the Flow rate (gpm), D_h is the hole diameter (in) (in cased hole, the inner diameter of the casing, in open hole the diameter of the bit), D_p is the outer diameter of the drillpipe.

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[1] Siruvuri C., Nagarakanti S., Samuel R. Stuck Pipe Prediction and Avoidance: A Convolutional Neural Network Approach. 2006. Presented at the IADC/SPE Conference, Miami, Florida, USA, 21-23 February 2006. SPE-98378-MS.

[2] Murillo A., Neumann J., Samuel R. Pipe Sticking Prediction and Avoidance Using Adaptive Fuzzy Logic and Neural Network Modeling. 2009. Presented at the 2009 SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA 4-8 April 2009. SPE-120128-MS.

2. Determination of Annular Pressure Losses (also apart for cased and open hole):

$$p_{an} = \frac{[(1.4327 * 10^{-7}) * \rho_m * L_{an} * v^2]}{D_h - D_{op}} \qquad \text{Eq. (8)}$$

where, p_{an} is the annular pressure loss (psi), ρ_m is the mud weight (ppg), L_{an} is the length of the annular (in total, when calculate, separately for open section and cased section) (ft).

3. Calculation of ECD:

$$ECD = \frac{\frac{p_{an}}{0.052}}{TVD} + \rho \qquad \text{Eq. (9)}$$

where, *ECD* is the equivalent mud density (ppg) and *TVD* is the vertical depth (ft).

4. Then, from the obtained ECD and the pore pressure gradient[1] calculate the differential pressure:

$$\Delta p = (\frac{ECD}{8.33} * 1000 * 9.81 - \nabla p_{pp}) * TVD \qquad \text{Eq. (10)}$$

where, g is the gravitational constant (Nm^2/kg^2), ∇p_{pp} is the pore pressure gradient (bar/m).

To get the relevant data, the differential pressures were determinated for bit depths.

Differential pressure depends on the following impressionable parameters:

- Flow rate
- Hole diameter (or casing diameter, thus casing seat depth)
- Pipe outer diameter
- Mud Weight

6.2.2 Static Time

In the database for the thesis, a column was made to describe the operation in every dataset. It could be: drilling, RIH, POOH, circulation or other operation. If there is no pipe movement, there could be two options: circulation or other operation. From that, the static time could easily determined with using IF function.

To decrease static time, keep the drillstring in move.

6.2.3 Formation

From the geological daily report, a database could built for the formation ranges, as the example screenshot shows below:

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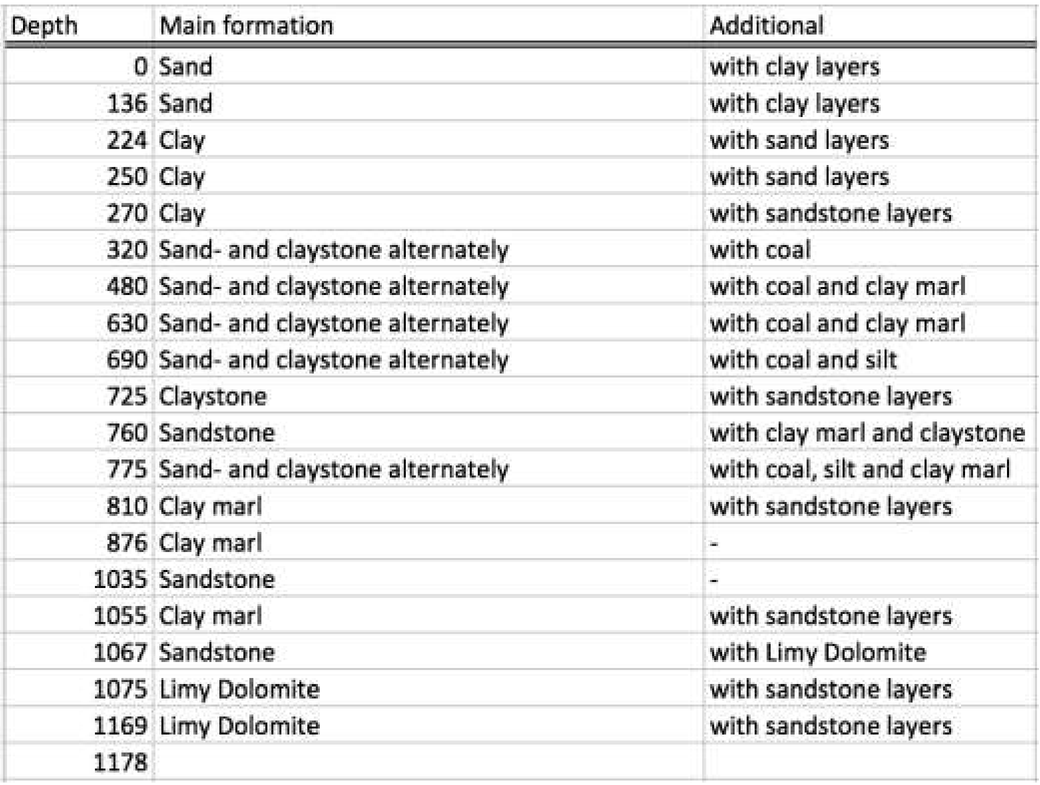
[1] Calculation method described in Appendix B



Depth	Main formation	Additional
0	Sand	with clay layers
136	Sand	with clay layers
224	Clay	with sand layers
250	Clay	with sand layers
270	Clay	with sandstone layers
320	Sand- and claystone alternately	with coal
480	Sand- and claystone alternately	with coal and clay marl
630	Sand- and claystone alternately	with coal and clay marl
690	Sand- and claystone alternately	with coal and silt
725	Claystone	with sandstone layers
760	Sandstone	with clay marl and claystone
775	Sand- and claystone alternately	with coal, silt and clay marl
810	Clay marl	with sandstone layers
876	Clay marl	-
1035	Sandstone	-
1055	Clay marl	with sandstone layers
1067	Sandstone	with Limy Dolomite
1075	Limy Dolomite	with sandstone layers
1169	Limy Dolomite	with sandstone layers
1178		

Figure 24: Formations in Ve-220 well

With this database, it could be order the proper formation for each depth with using the VLOOKUP function. The formation appears in the same form as in the geological report, so there is one main formation and there are some additional formations, if there is any.

Of course, we can not influence the formation.

6.2.4 Flow Pattern

Regarding to Adams[1] flow pattern could be a driver factor to avoid differential pressure sticking. To determine the flow pattern, the following method was used:

1. Determine the Hedstrom number of the flow:

$$N_{He} = \frac{24700 * \rho_m * \tau_y * (D_h - D_{op})}{\mu_p^2} \qquad \text{Eq. (11)}$$

where ρ_m is the mud weight (ppg), τ_y is the yield point (lb/100ft^2), D_h is the hole diameter (in) (in cased hole, the inner diameter of the casing, in open hole the diameter of the bit), D_p is the outer diameter of the drillpipe (in), and μ_p is the plastic viscosity (cP).

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[1] Adams N. 1977. A Field Case Study of Differential-pressure Pipe Sticking. Presented at the 52nd Annual Fall Technical Conference and Exhibition of the SPE, Denver, Colorado, USA, 9-12 October 1977. SPE-6716-MS.

2. Read off the critical Reynolds number from the following Figure by Hanks[1]

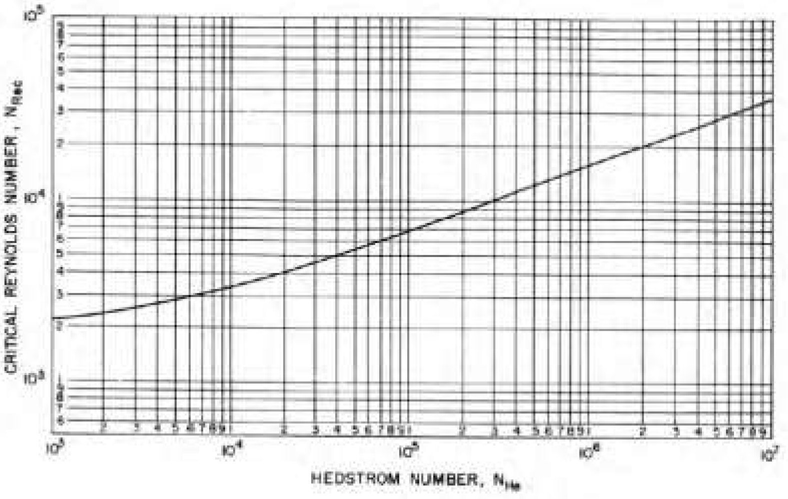

Figure 25: Critical Reynolds number for Bingham fluids[2]

3. Determine the actual Reynolds number of the flow

$$N_{Re} = \frac{757 * \rho_m * \bar{v} * (D_h - D_{op})}{\mu_a} \qquad \text{Eq. (12)}$$

where $\bar{v}$ is the mean velocity (ft/s), what could be calculated with the following equation:

$$\bar{v} = \frac{Q}{2.448(D_h^2 - D_{op}^2)} \qquad \text{Eq. (13)}$$

where Q is the Flow rate (gpm), D_h is the hole diameter (in) (in cased hole, the inner diameter of the casing, in open hole the diameter of the bit), D_p is the outer diameter of the drillpipe;

and μ_a is the apparent viscosity (cP), what could be calculated with the following equation:

$$\mu_a = \mu_p + \frac{5\tau_y(D_h - D_{op})}{\bar{v}} \qquad \text{Eq. (14)}$$

4. Compare the actual Reynolds number to the critical Reynolds number; if the the actual greater, the flow pattern is turbulent, of the critical is the greater, the flow pattern is laminar.

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[1] Hanks R.W. and Pratt D. R. „On the Flow of Bingham Plastic Slurries in Pipes and Between Parallel Plates." *Soc. Pet. Eng. J.* (Dec. 1967) 342-46. *Trans.* AIME. **240**

[2] Bourgoyne A. T., Millheim K.K., Chenevert M. E., Young Jr. F.S. 1986. "Applied Drilling Engineering". Richardson, Texas, USA: Textbook Series, SPE.

Flow pattern depends on the following impressionable parameters:

- Mud weight
- Yield Point
- Plastic viscosity
- Hole diameter (or casing diameter, thus casing seat depth)
- Pipe outer diameter
- Flow rate

6.2.5 Well Trajectory Factors

To describe the well trajectory, the method of Murillo et al was followed partially. For this, they used the depth ratio, which is the ratio of the measured and true vertical depth. The author extended the depth ratio with the dogleg, inclination angle and the open hole length.

These parameters, we hardly could change during drilling, but it could be changed in the planning phase.

6.2.6 Mud and Mudcake Parameters

With mud parameters, the author did not use ratios, because in his opinion, the actual values are important. For example, Murillo et al, used Gel Ratio, from 10 min Gel Strength divided by 10 s Gel Strength, this thesis author rather used the two parameter independently.

The mud parameters what were used in this model the following:

- 10 min Gel Strength
- 10 s Gel Strength
- Mud Weight
- Plastic Viscosity
- Yield Point
- Calcium Filtrate
- Chloride Filtrate

Because this thesis is about an analysis based on real event from the past, it is not a real-time prediction, the author thought that there is a need for some extra information about the mudcake. In all three cases of this thesis, the sticking occurred after drilling, during some other operations, so the mudcake was older when the problem occurred.

Therefore, it was considered that the mudcake has different properties than the actual formation. So, the mudcake parameters come from the mud properties from that time this depth was drilled. Furthermore, the mudcake age and the differential pressure from drilling were also determined.

Mudcake parameters:

- 10 min Gel Strength
- 10 s Gel Strength
- Mud Weight
- Plastic Viscosity
- Yield Point
- Calcium Filtrate
- Chloride Filtrate
- Differential Pressure
- Mudcake Age

Mudcake parameters, of course can not be modified afterwards, but every mud parameter could be.

6.2.7 BHA section

In term of contact area, BHA section is a determining factor. Based on the drilling daily reports, BHA data were collected for every dataset. BHA parameters are the following:

- Length of BHA section
- Number of DCs
- DC diameter
- HWDP diameter
- DP diameter

Parameters of BHA could not be changed suddenly, but could be in relatively short time.

6.2.8 Other drilling parameters

In this section, the actual drilling regime was considered. Drilling Parameters:

- ROP
- WOB
- Hookload
- Torque
- Pump pressure
- Mud Flow rate

Every drilling parameter could be modified real-time.

6.2.9 Other parameters

There are some other parameters and method, which is proven that works, but could not be modeled with NeuralTools because, we do not have data with it. These are the following:

- Generic mud type
- Exact BHA composition
- Solids Control Equipment

6.3 Model Training Results

Cumulatively the collected data from the three wells gives 17406 datasets for neural network modeling. The NeuralTools gives a recommendation for modeling by analyzing the dataset. In this case, the recommendation was to use PN/GRN Net, what means Probabilistic Neural Net if the dependent variable is a category, or Generalized Regression Neural Net, if the dependent variable is numeric. In this case, that meant PN net.

Because the created database was high enough, the option of “automatically test on randomly selected cases 20% of the database” was chosen.

The model made up from 36 independent numeric and 8 independent category variables, and should be able to predict one dependent category, which is the sticking status.

The overall number of cases minus the 20% for testing gives the number of training datasets, it was 13925. The training ran trouble-less, and auto-stopped at the end. During the training session, 67 trials was done.

During the testing phase, 3481 cases was tested, and the final result was 0.0575% bad predictions. It means 2 bad predictions out of 3481 cases. The detailed result of the training of the net could be seen in Table 20, which was made with a built-in function of the NeuralTools.

Table 20: Summary report of Neural Network Training

Summary	
Net Information	
Name	Net Trained on Differential Sticking Probability Analysis
Configuration	PNN Category Predictor
Location	This Workbook
Independent Category Variables	8 (Well #, Operation, Formation at bottom main, Formation at bottom additional, Formation at bit depth main, Formation at bit depth additional, Mudcake place, Flow Pattern)
Independent Numeric Variables	36 (Depth [m], TVD [m], Bit Depth [m], Pore Pressure, ROP [m/h], WOB [t], Hookload [t], Torque [Nm], Pump Pressure [bar], Mud Flow Rate [l/min], 10 min Gel Strentgh [lb/100ft2], 10 s Gel Strentgh [lb/100ft2], Mud Weight [sp. Grav.], Plastic Viscosity [cP], Yield Point [lb/100ft2], Calcium Filtrate [mg/l], Chloride Filtrate [mg/l], Static Time, Mudcake 10 min Gel Strentgh [lb/100ft2], Mudcake 10 s Gel Strentgh [lb/100ft2], Mudcake Mud Weight [sp. Grav.], Mudcake Plastic Viscosity [cP], Mudcake Yield Point [lb/100ft2], Mudcake Calcium Filtrate [mg/l], Mudcake Chloride Filtrate [mg/l], Mudcake Differential Pressure [bar], Differential Pressure at Bit Depth [bar], Dogleg Rate [°/30m], Open Hole Length [m], Inclination [°], Length of BHA section [m], Number of DCs, Diameter of DC [in], Diameter of HWDP [in], Diameter of DP [in], Mudcake age (min))
Dependent Variable	Category Var. (Sticking status)
Training	
Number of Cases	13925
Training Time	1:25:46
Number of Trials	67
Reason Stopped	Auto-Stopped
% Bad Predictions	0.0072%
Mean Incorrect Probability	0.0179%
Std. Deviation of Incorrect Prob.	0.7672%
Testing	
Number of Cases	3481
% Bad Predictions	0.0575%
Mean Incorrect Probability	0.0757%
Std. Deviation of Incorrect Prob.	2.3220%
Prediction	
Number of Cases	5
Live Prediction Enabled	YES
Data Set	
Name	Differential Sticking Probability Analysis
Number of Rows	21292
Manual Case Tags	NO

6.4 Analysis of Sticking Situations

This subchapter contains the analysis and possible solution methods of the three differential sticking situation successively.

6.4.1 TUS-80

The sticking occurred in this well during RIH for wiper trip at 2169 m MD. To see the whole process, the author investigated also the drilling of this section, when analyze.

The four criteria of the sticking could be clearly seen, they are underlined in the concerning chapter, namely:

- breccia with limestone and metamorphic metaclaystone main grains » permeable formation
- fluid loss to the formation » enough differential pressure
- cuttings in mud » developed mudcake
- make a connection » static time

The problematic breccia formation could not be found any of the other two wells. The target layer is below this formation, a metamorphic rock from Paleozoic. The breccia layer is between 2062 m and 2167m in vertical depth. This mean that the formation is in the well's tangent section, with 25.56° average inclination and 1.25 °/30m dogleg. The kick off point is at 1370 in a clay marl layer. This clay marl layer continued from 1240 m, so the kick off point could be 1240m safely. If the kick off point is higher, the average inclination angle could be lower in the problematic zone, as well as the length of the well in this formation could be lower. In the author's opinion, it is could be one possible modification, what has effect on sticking tendency.

Therefore, the trajectory of the well was recalculated with tangential method[1], and the following result was got:

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[1] Calculation method described in Appendix B

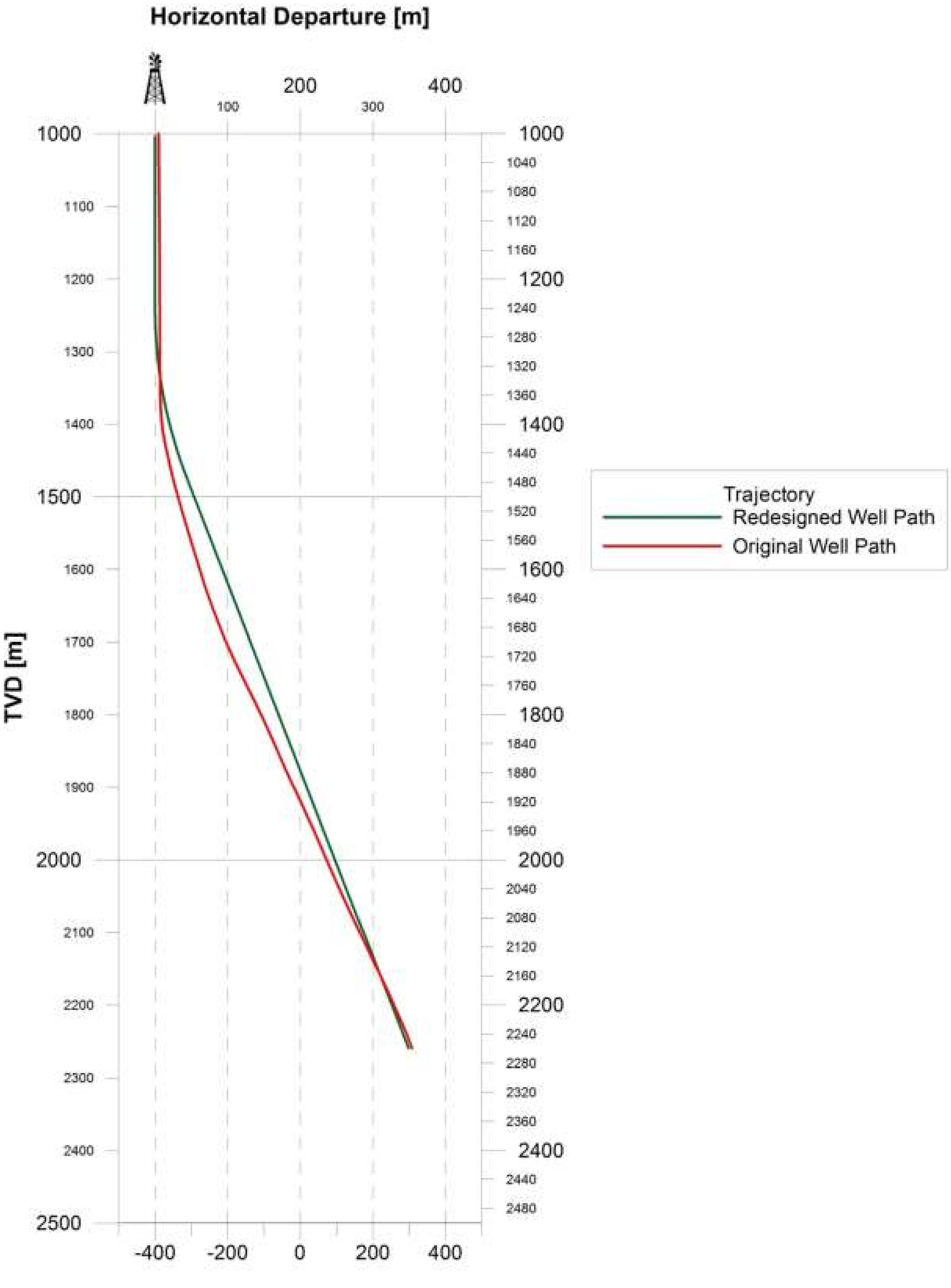

Figure 26: Redesigned and Original Well Path for TUS-80 well

Table 21: Comparison of Original and Redesigned well path from the view of the problematic formation in TUS-80

	Actual Well Path	**Redesigned Well Path**
Breccia Formation TVD (m)	2062 - 2167	2062 - 2167
Breccia Formation MD (m)	2113 – 2228	2111 – 2221
Length of Breccia Formation (m)	115	110
Average Inclination (°)	25.56	21.245
Dogleg Severity (°/30m)	1.25	0

During the drilling of the section, fluid loss to the formation was observed. The differential pressure at 2169m was 20 bar. For decrease the fluid loss effect, $CaCO_3$ was added to the mud, but the efficiency was various. In the breccia formation, the fluid loss could have stopped, but it started again in the metamorphic rock formation. The differential pressure was between 20 bar and 24 bar when the last formation was drilled.

Having examined the mud window, using the pore pressure- and the fracture gradients, and it was found, that they are used a conservative 3% safety margin when planned the mud weights. Therefore, the differential pressure could be lowered if we use a smaller safety margin, as 1%, for the problematic casing section.

Table 22: Comparison of the Original and the Redesigned Mud Weight values in TUS-80

Casing Shoe TVD (m)	**Original Mud Weights (kg/m^3)**	**Redesigned Mud Weights (kg/m^3)**
30	1060	1060
1161	1150	1150
2259	1150	1115

As you can see in the Figure 27, only the last casing section’s mud weight, where the problem occurred, was changed. With this small, 0.035 s.g. change in mud weight result 7.5 bar differential pressure decrease at sticking depth.

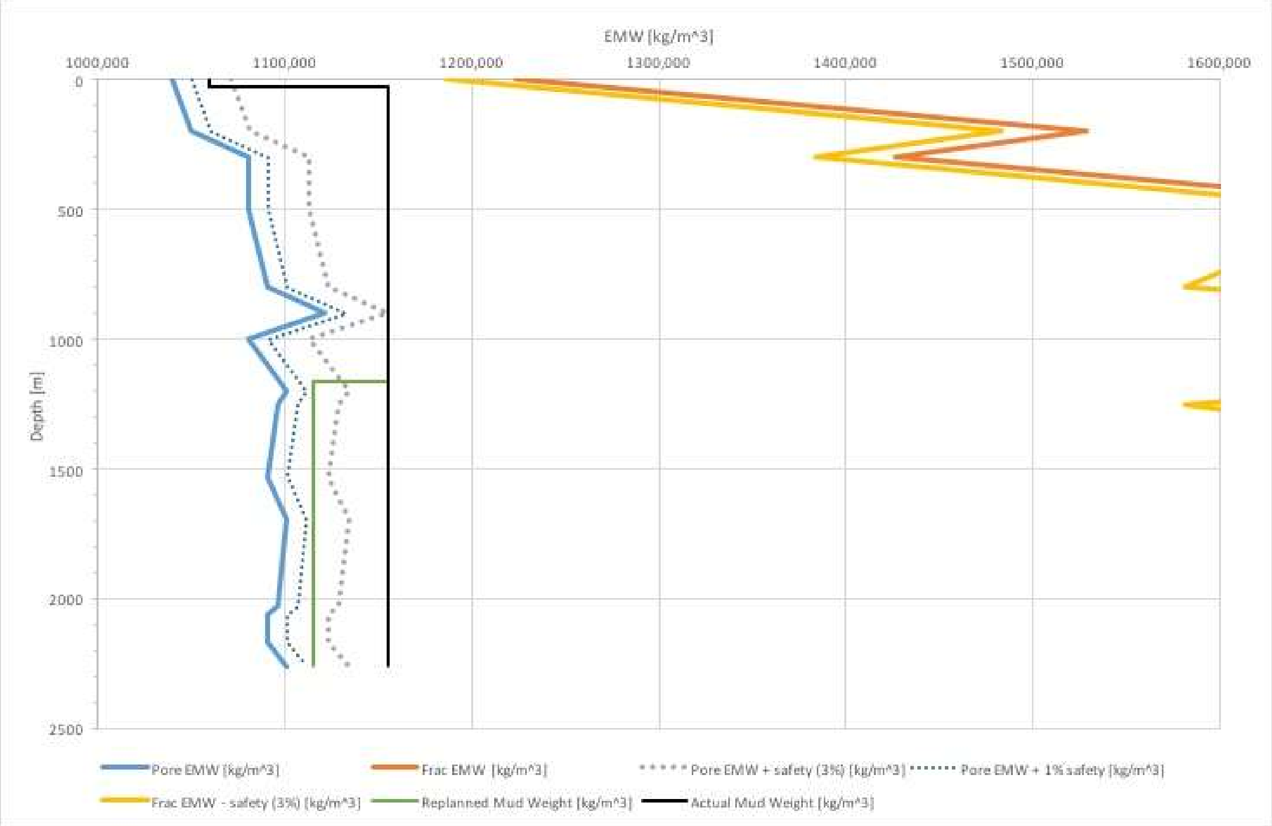

Figure 27: Original and Redesigned Mud Weight in TUS-80

Although fluid loss occurred, as it was calculated, there were only laminar flow during the drilling. When the fluid started to migrate into the formation, $CaCO_3$ was added to the mud. This was not a perfect solution, because the fluid loss started again few times, no avail more $CaCO_3$ was added.

The problem maybe come from the fact that the grain size of the $CaCO_3$ was not proper to the pore size. Because there is no information about comeback $CaCO_3$ the author came to the conclusion that the grain size was too small, and recommends a bigger grain size loss circulation additive, for example nut shell, which has a 0.25” maximal grain size, instead of $CaCO_3$’s 0.12”.

If the fluid loss could be stopped, it should be considered to change the flow pattern form laminar to turbulent. It would help to keep the mudcake thin enough to avoid sticking.

The effect of changes of every parameter on flow pattern were investigated. The results are plotted in the following Figure.

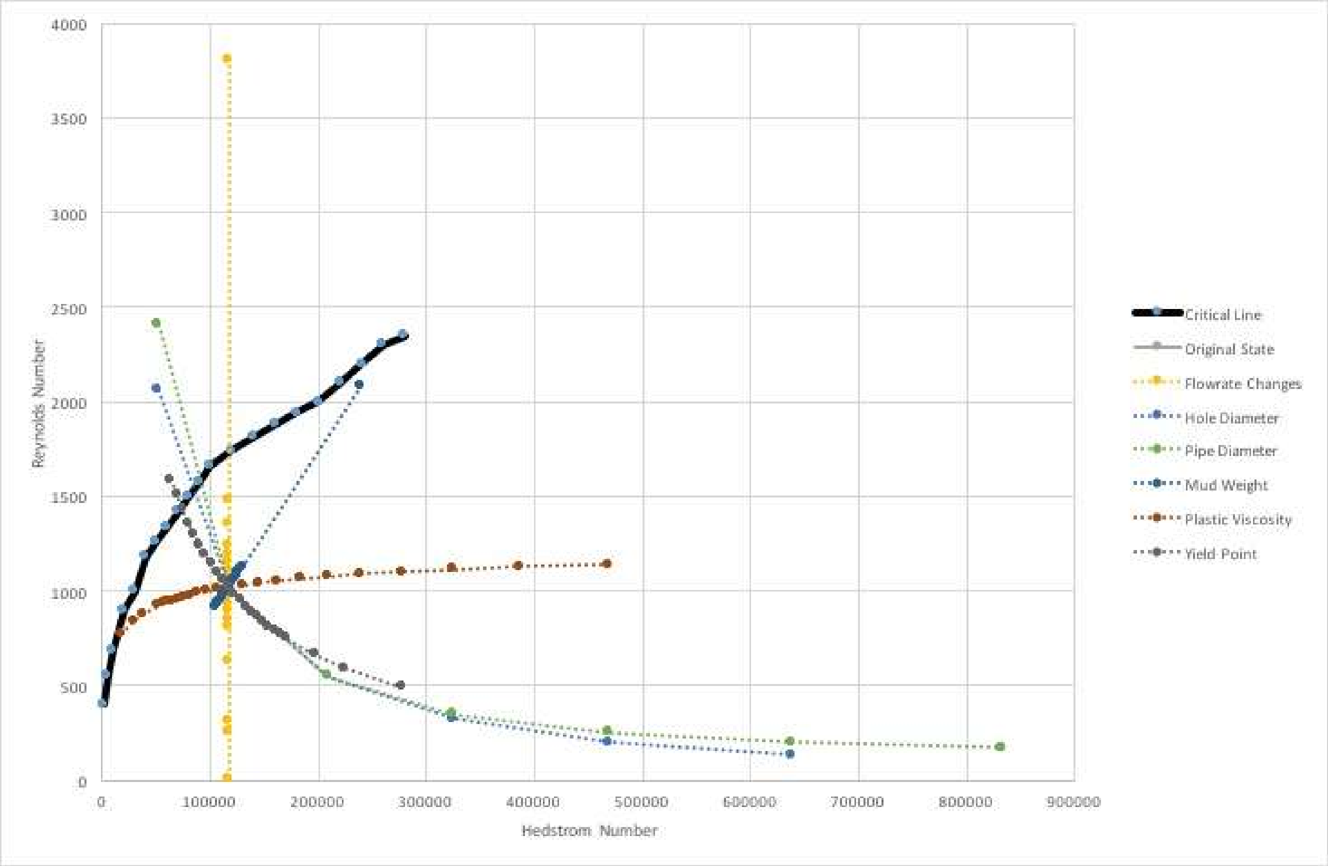

Figure 28: How the different parameters affect flow pattern

In the Figure it can be seen the critical Reynolds number line. If the actual Reynolds number is below this line, the flow is laminar, if it is above the flow is turbulent.

From the plotted parameters, consider the hole diameter and the mud weight (because it was calculated earlier) fix. Also, mud weight does not really effect the flow pattern by itself, the Reynolds number changes in nearly a parallel with the critical line. Then, we could change the drillpipe diameter, the Flow rate, plastic viscosity and yield point.

At this point, the author would like to indicate that from these parameters, the drillpipe diameter and the flow rate also have effect on differential pressure, so it should be considered prior changing them. In the following Figure could be seen the effect of the Flow rate and the pipe diameter on differential pressure at 2169m MD.

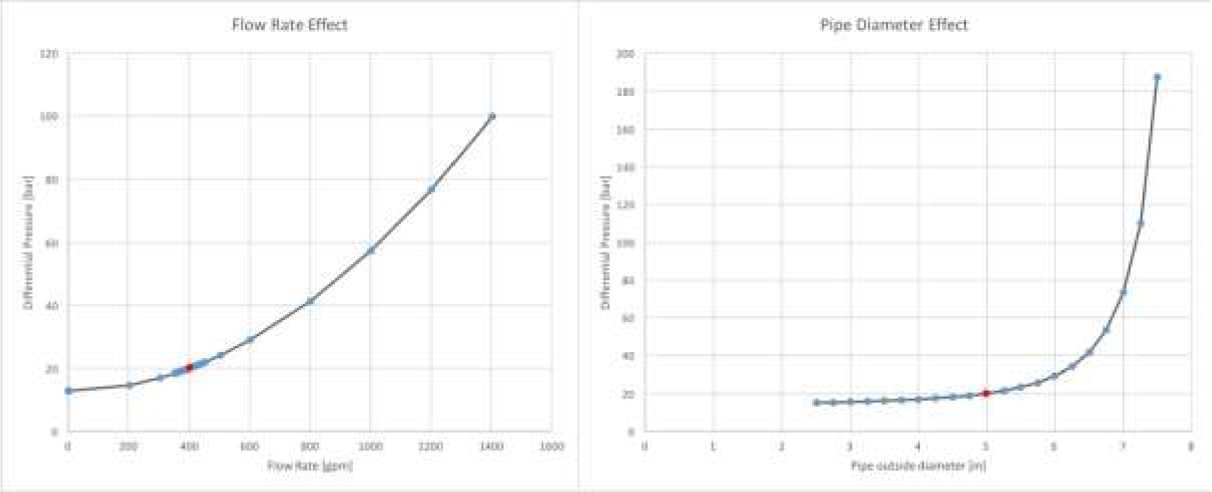

Figure 29: Effect of Flow Rate and Pipe Diameter changes on Differential Pressure

As could be seen, the pipe diameter has a huge effect on differential pressure, especially at small clearance, nearly the same as on the flow pattern. So, in author's opinion it does not worth to increase the pipe diameter. Flow rate is increase much more profitable, but only minor or moderate extent.

With the new mud weight, the fixed hole and pipe diameter, and the changeable flow rate, plastic viscosity and yield point, the new mud regime were determinate to achieve turbulent flow in the well. The author considered to keep the differential pressure lower than the original value. The following Table contains the reliable mud parameters for the new and for the original muds.

Table 23: Mud parameters for the redesigned and the original mud in TUS-80

	Original Mud	**New Mud**
Flow rate (l/min)	1524.4	2150
Hole diameter (in)	8.5	8.5
Pipe outside diameter (in)	5	5
Mud weight (s.g)	1.15	1.115
Plastic Viscosity (cP)	22	18
Yield Point (lb/100ft^2)	24	14
Differential Pressure @ 2169m	20.0	19.4

The Figure 30 shows that the new mud states in the turbulent flow pattern zone, instead of the original mud's laminar flow state.

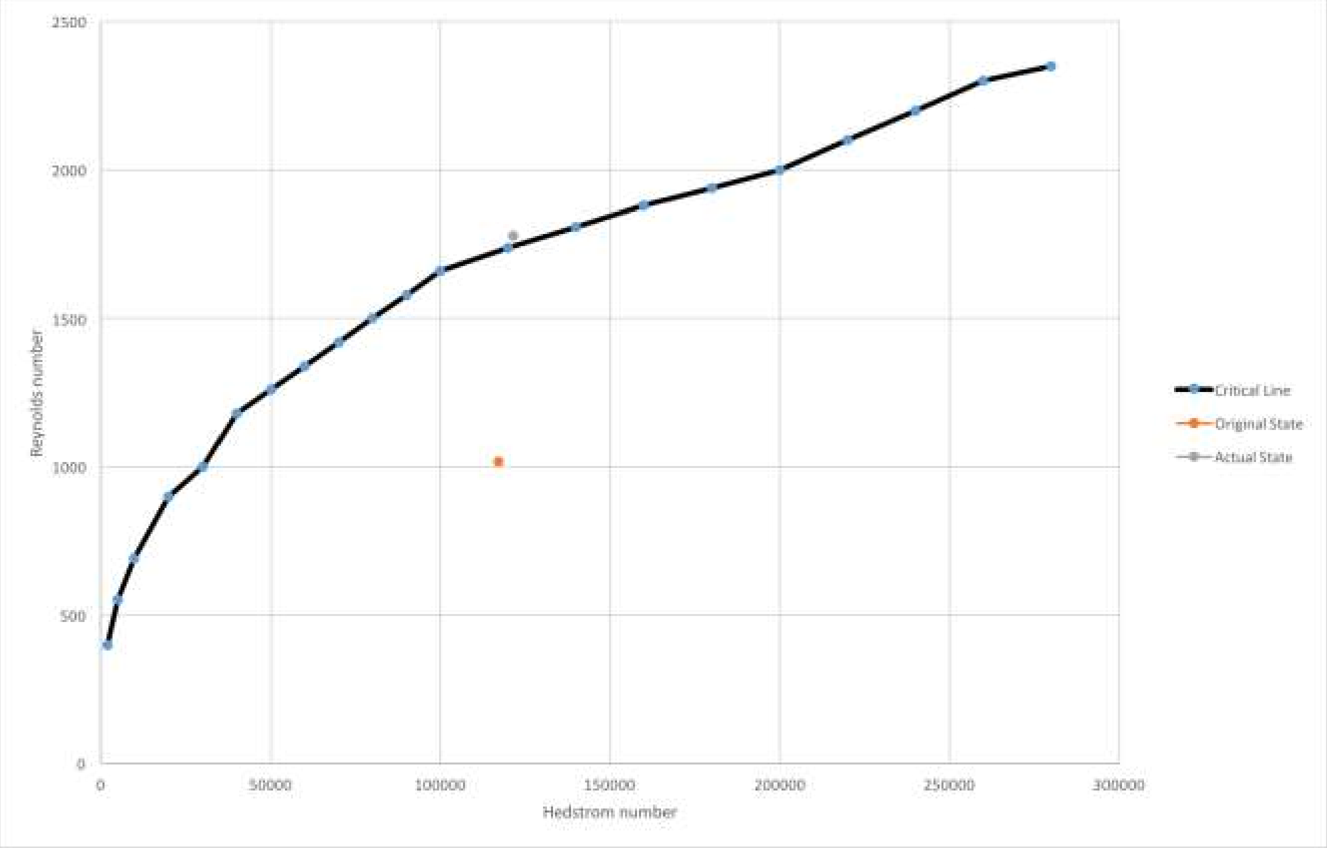

Figure 30: Flow Pattern state for the new mud in TUS-80

The yield point value could be seemed slightly low to carry the cuttings, but it is associated with a great flow velocity, so it would not cause problem. If the fluid loss could not be prevented, with these parameters easily could change the flow pattern back to laminar, with decreasing the flow rate and even increasing the yield point. This operation would decrease the differential pressure at the same time.

Another parameter to investigate is the BHA. When the sticking occurred, the planned operation was RIH for wiper trip. The table below contains the detailed BHA.

Table 24: BHA at sticking situation in TUS-80

Size (in)	Item	Length [m]
8 ½”	PDC Bit	0.26
8 1/8”	Stabilizer	1.78
6 ½”	DC	18.46
8 ¼”	Stabilizer	2.39
6 ½”	DC	54.85
6 ½”	Jar	5.2
6 ½”	DC	18.62
5”	HWDP	111.4
5”	DP	1969.32

As could be seen, although there was only wiper trip planned, the BHA made up with numerous DCs. The maximum WOB was 7.2 t during the operation. This could be achieved by using only the HWDPs in the BHA section. If we use one DC to stabilize the BHA, and a jar for safety, the new BHA is still smaller than the original. With the new mud it means that the length of the BHA is 149.36 m instead of 212.96 m.

Table 25: Redesigned BHA section for TUS-80

Size (in)	Item	Length [m]
8 ½”	PDC Bit	0.26
8 ¼”	Stabilizer	2.39
6 ½”	DC	9.23
6 ½”	Jar	5.2
5”	HWDP	132.28
5”	DP	2020.84

Static time was when sticking, but it was not too long, just a normal connection time, in this case was not more than 2 minutes. In the author's opinion, it could not be lowered.

At solids control, they made a mistake, when the centrifuge was turned off to keep the cuttings in the mud to reduce fluid loss. Drilling cuttings are unreliable both in term of size and exact behavior. The proper action would be to use the centrifuge further and solve the fluid loss problem other way, what was described earlier.

In term of generic mud type, of course they could not use oil-based mud, but they used gypsum-poly mud, what is the second best choice after oil-based mud.

As an overview, the Table 26 shows my changes to the original sticking situation in the mode.

Table 26: Changes made on neural network model at sticking situation in TUS-80

	Original	**Recommendation**
Measured Depth @ bit [m]	2169.62	2165
Measured Depth @ bottom [m]	2330	2322
Inclination angle [°]	23.22	21.245
Dogleg Rate [°/30m]	0.9	0
Mud Weight [s.g.]	1.15	1.115
Plastic Viscosity [cP]	19	18
Yield Point [lb/100ft^2]	18	14
Differential Pressure [bar]	17.49	10.11
Mud Weight @ drilling [s.g.]	1.15	1.115
Plastic Viscosity @ drilling [cP]	22	18
Yield Point @ drilling [lb/100ft^2]	24	14
Differential Pressure @ drilling [bar]	20	19.4
Length of BHA [m]	212.96	149.36
Number of DCs	10	1

With the described changes, the neural network model predicted the situation as non-sticking with 88.48% probability. Taking into account, that the model had 0.0575% bad predictions at testing phase, the situation could be considered as non-sticking with the introduced changes.

6.4.2 Mk-X3 St-1

In this well, the analysis was also started with the four criteria of the differential sticking.

- permeable formation » clay marl with sandstone layers
- enough differential pressure » after the sticking, the company man requested to lower the mud weight from 1.13 to 1.1 s.g. No problem was caused, so the original mud weight was too high.
- developed mudcake » improper hole cleaning, cuttings in the mudcake
- static time » logging session, extra long static time of 1 hour

In author's opinion, the main responsible factor for sticking is the weak hole cleaning and the high mud weight. Thus, the most important step was to determine the cutting transport ratio, with Chien's correlation[1]. The cuttings ratio was 81%, what could be improved. Unfortunately, static time, although it was quite long, could not be lowered, because the logging takes fix time.

For the analysis, the author followed the method, what did at the analysis of TUS-80. First of all, began with the well trajectory.

The sidetrack was drilled from 750m, below the casing shoe at 702m. The KOP moved to slightly below the casing shoe at 705m. This was the only modification what was made, and the results could be seen in the Figure 31.

Lower inclination angle helps to transport the cuttings, in high inclination wells, cuttings settle down to the lower side of the borehole.

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[1] Calculation method described in Appendix B

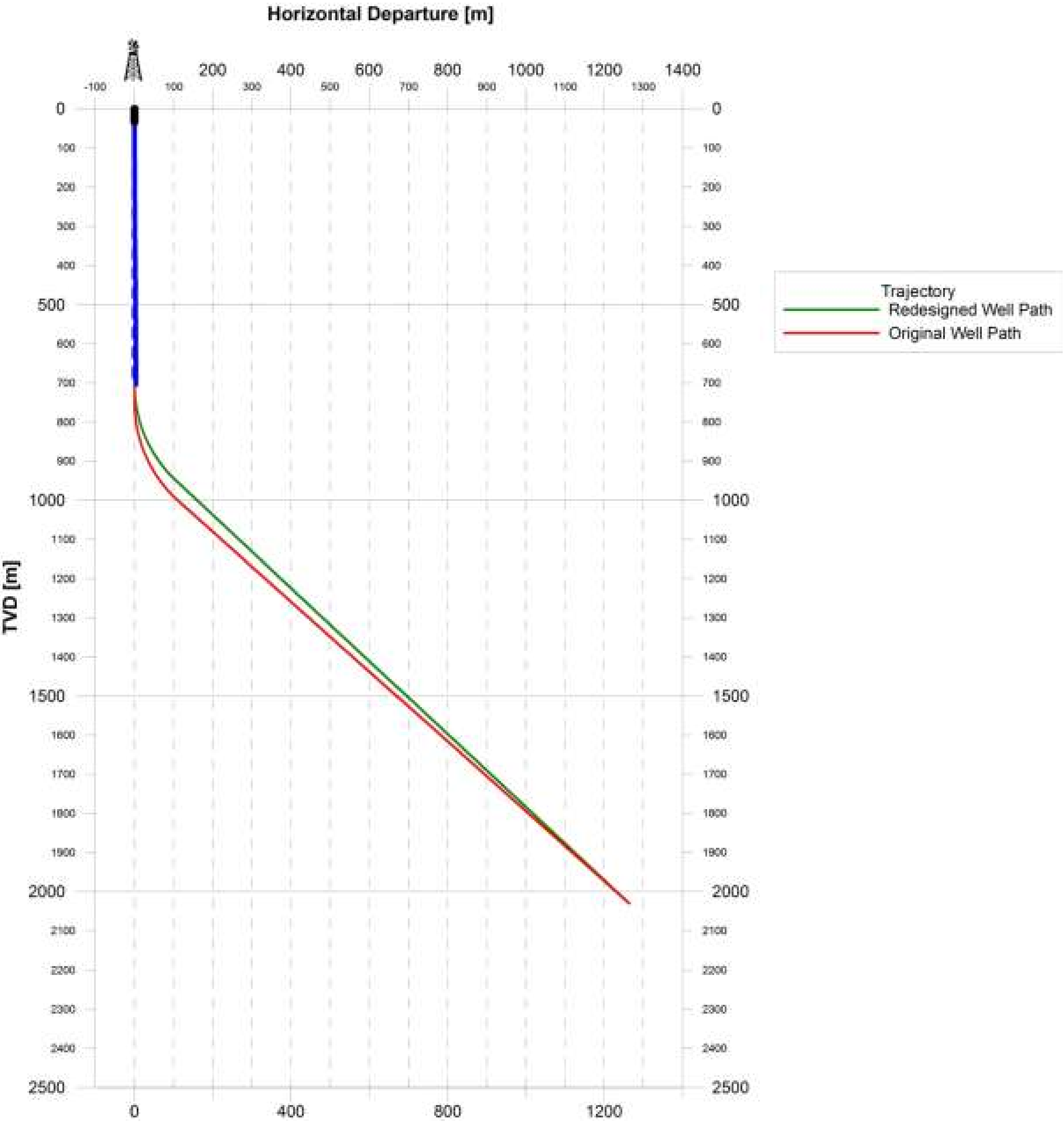

Figure 31: Redesigned and Original Well Path for Mk-X3 St-1 well

With this modification, the total measured depth decreased from 2578m to 2563m, and the inclination angle at the bottom of the well decreased to 47° from 48.25°.

Because there was no fluid loss problem in the well, the turbulent flow pattern could be advised. It helps in the cuttings transport and also controls the mudcake. So, the main purposes were to improve cuttings transport ratio and achieve turbulent flow to prevent cuttings settling, with striving to keep the differential pressure low.

The first step was to check the mud weight window with the calculated pore pressures. Similar circumstances were found like the previous, TUS-80 well. The safety factor for mud designing was also 3%, what is too high in differential sticking dangerous zone. A more reasonable 1% safety factor was used. The result could be seen in Figure 32 and Table 27.

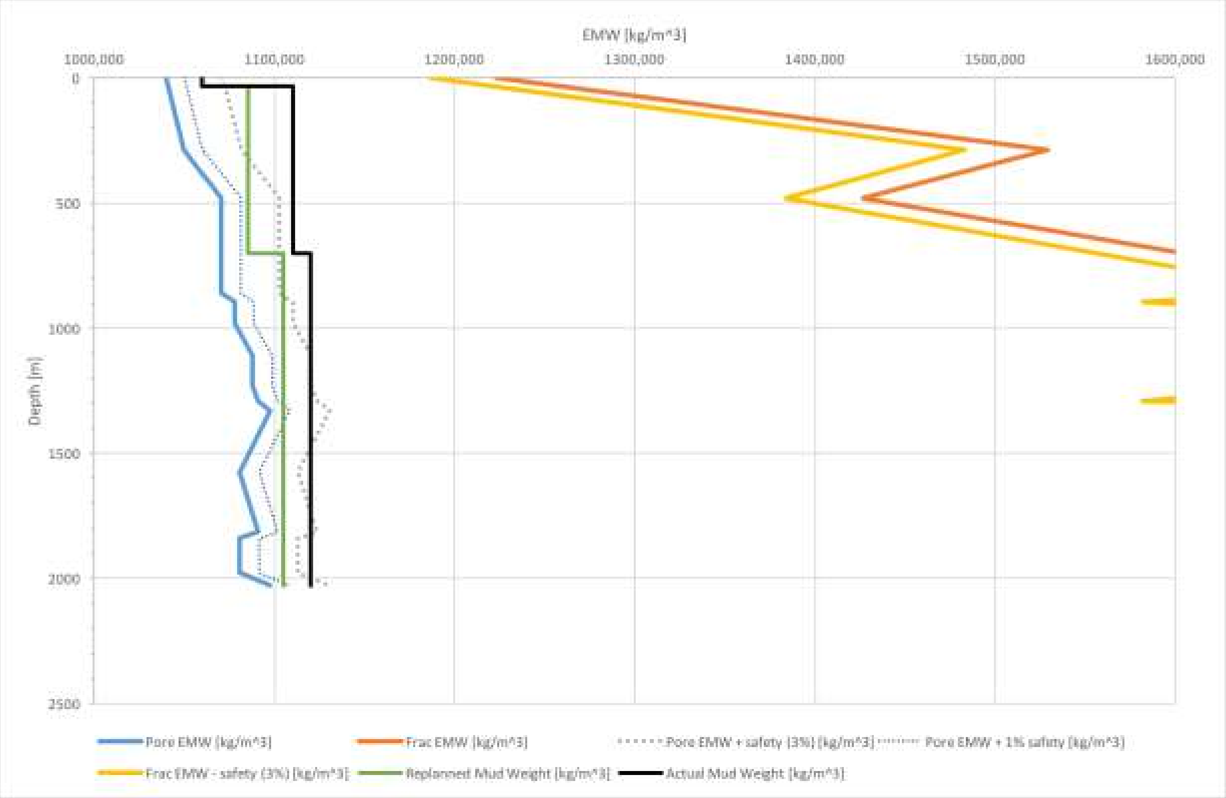

Figure 32: Original and Redesigned Mud Weight in Mk-X3 St-1

The differential pressure with the original mud at the drilling of the bottom of the well was 19.53 bar. When the sticking occurred, it was 8.18 bar.

Table 27: Comparison of the Original and the Redesigned Mud Weight values in Mk-X3 St-1

Casing Shoe TVD (m)	Original Mud Weights (kg/m^3)	Redesigned Mud Weights (kg/m^3)
30	1060	1060
750	1110	1085
2030	1120	1105

If the new mud weight had determined, the next step was to ensure that the borehole could be cleaned. As it was stated above, it would be by using turbulent flow and increase transport ratio, while the differential pressure kept as low as possible.

The transport ratio depends, as well as the flow pattern, on:

- Flow Rate
- Hole Diameter
- Pipe Outer Diameter
- Mud Weight
- Plastic Viscosity
- Yield Point

From these parameters, hole diameter, pipe diameter, and mud weight were fixed, as was done at the analysis of the TUS-80 well. The radius of the cuttings considered as 0.5” and the density of the clay marl is 18.72 ppg.

Then, the effect of the three parameter, flow rate, plastic viscosity and yield point were investigated on the flow pattern and also on the transport ratio. It is really difficult to state how influence a parameter the flow pattern, because for it, we need the critical Reynolds number line. But, as a role of thumb, we could say that the higher Reynolds number represents a more turbulent characteristic flow.

In the first Figure of this topic could be seen the the effect of the flow rate on the Reynolds number and on the cuttings transport ratio. As shown in the Figure 33, if we increase the flow rate it will increase both the Reynolds number of the flow and the transport ratio.

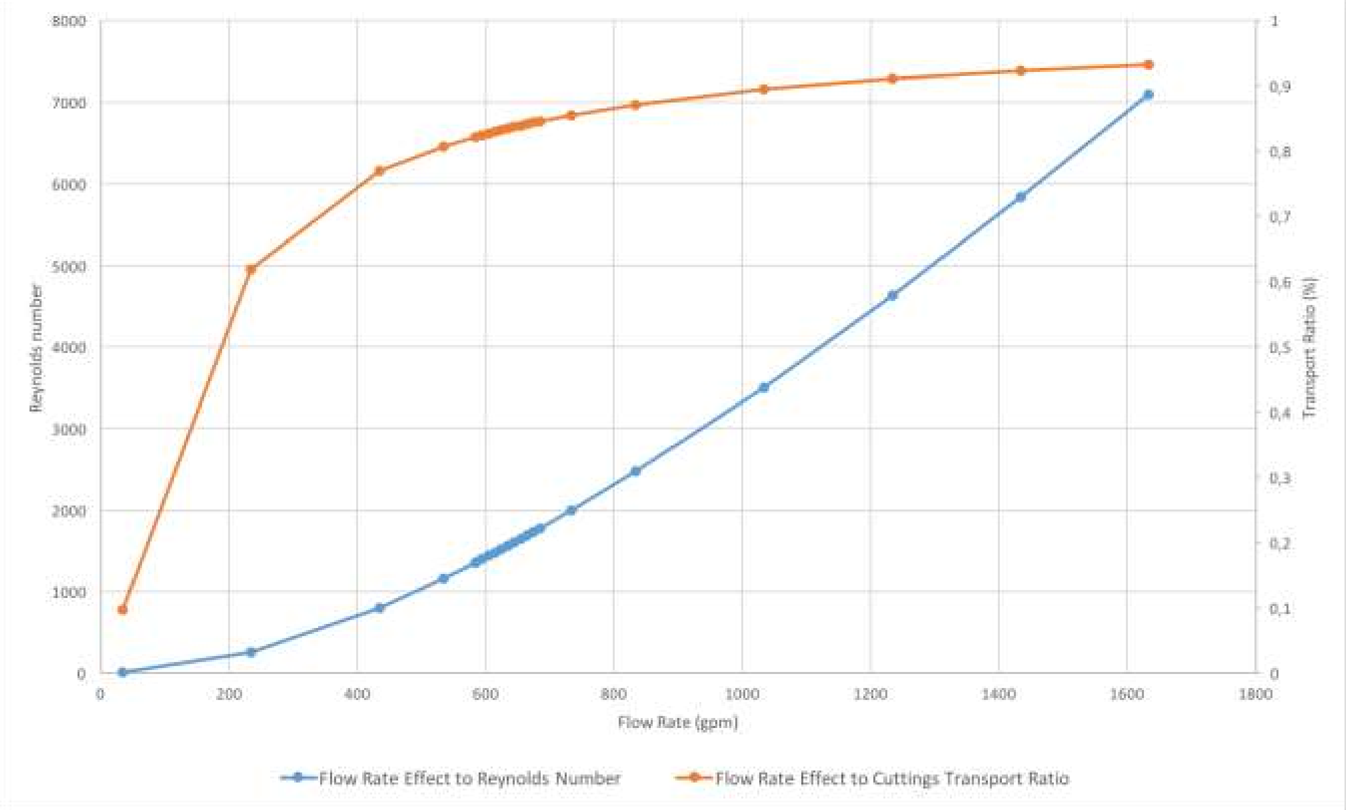

Figure 33: Effect of the Flow Rate changes on Reynolds number and cuttings transport ratio

The second picture (Figure 34) represents the effect of the plastic viscosity changes.

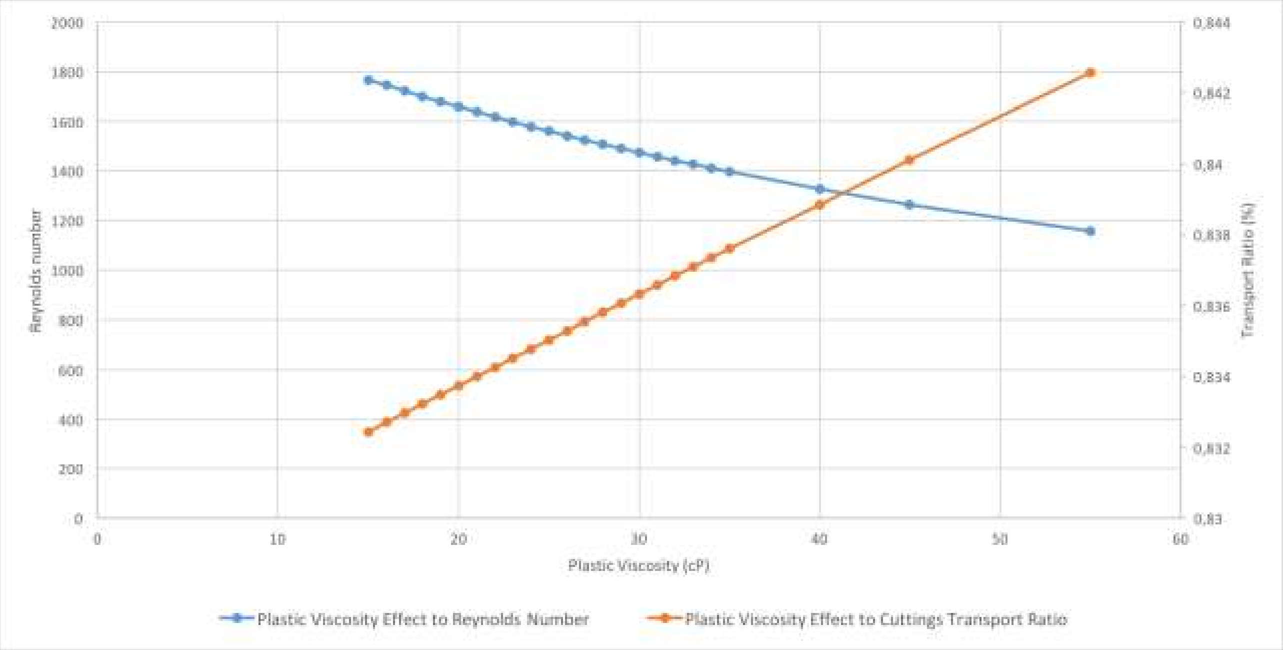

Figure 34: Effect of the Plastic Viscosity changes on Reynolds number and cuttings transport ratio

As could be seen, the plastic viscosity is inversely proportional to Reynolds number and directly proportional to the transport ratio. But both of them in a relatively small scale. 40 cP changes in plastic viscosity, causes 0.12% in transport ratio and 550 in Reynolds number.

The Figure 35 shows, that Yield Point changes induce same situations, but in a bigger scale. Unfortunately, if we adjust the yield point to increase transport efficiency, we could never make a turbulent flow.

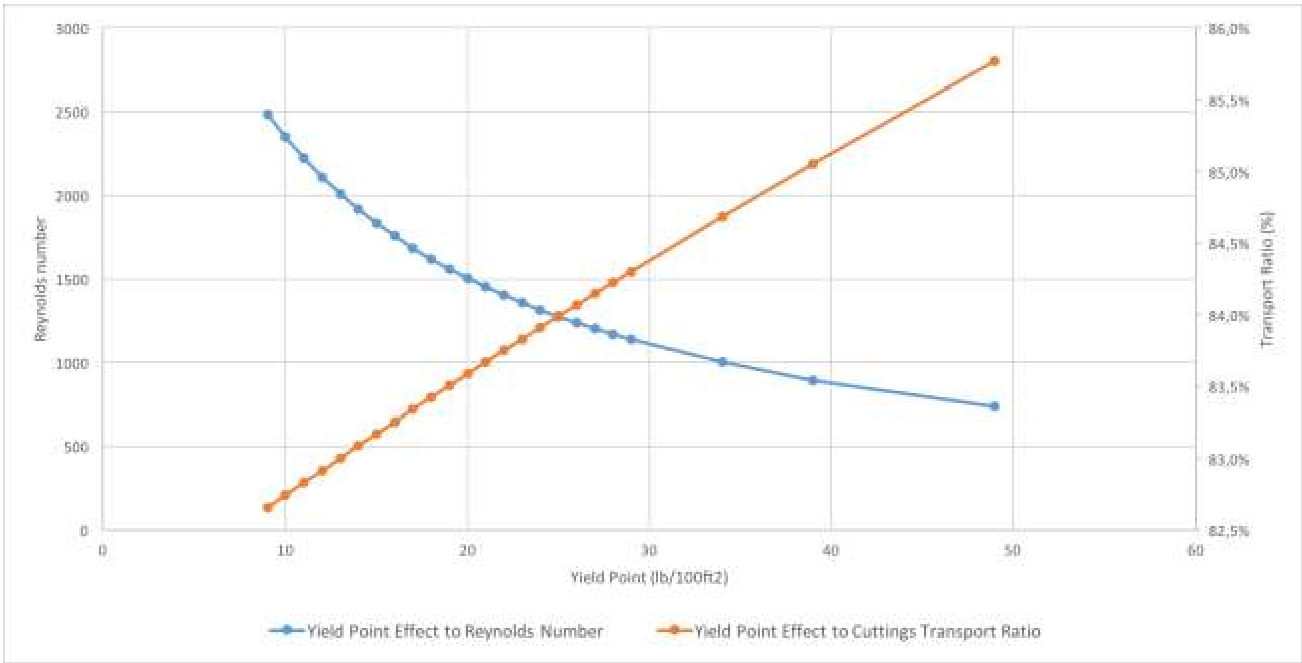

Figure 35: Effect of the Yield Point changes on Reynolds number and cuttings transport ratio

Thus, the method was to achieve a turbulent flow with changing the parameters, while keeping the yield point as high as it could be, then check the differential pressure and if there is a gap, increase the flow rate to increase the transport ratio.

According to these guidelines, a turbulent flow pattern could be achieved, 3% increase in transport ratio while the differential pressure increase is only 1.83 bar. If the flow pattern, or the differential pressure would cause fluid loss problem, it is easily to change back to laminar flow with much lower differential pressure, if the flow rate decreased by the crew. To illustrate it, an extra point was put to the Figure, using 2100 l/min flow rate instead of the determined 2400 l/min.

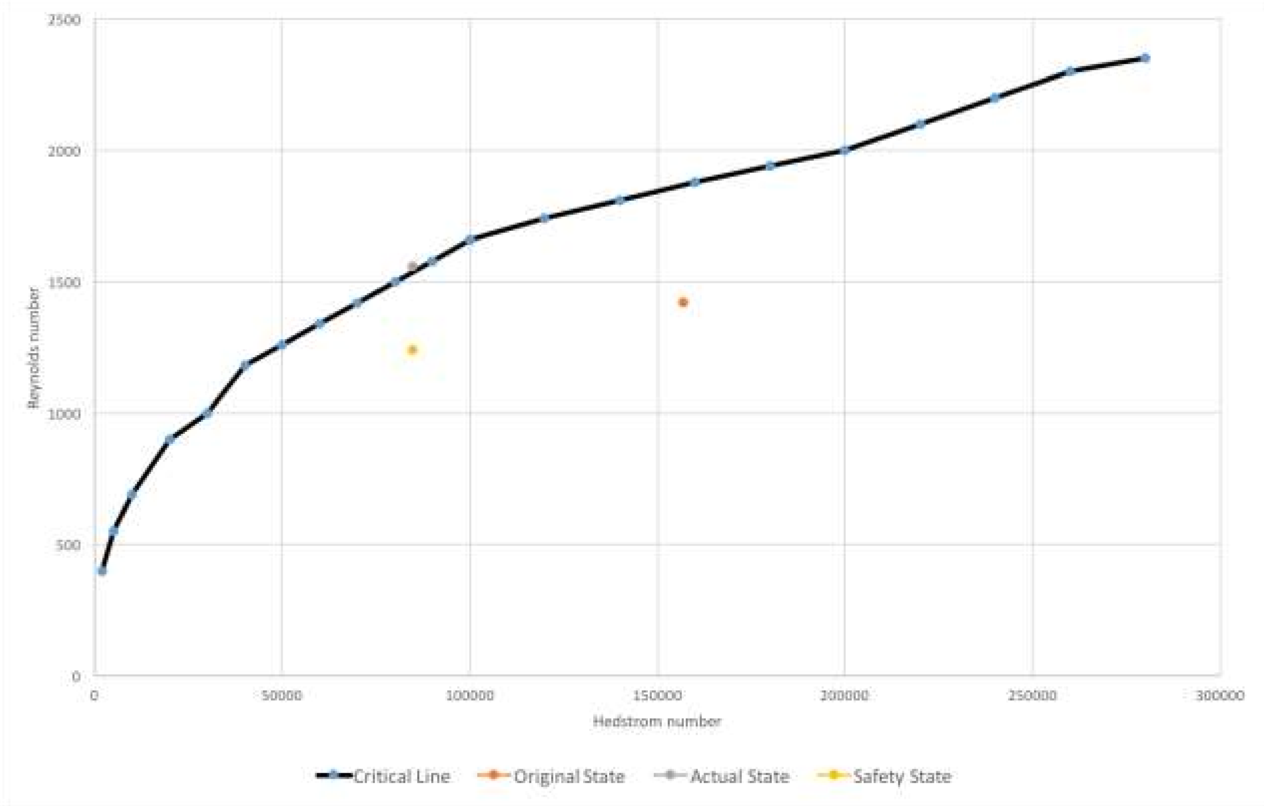

Figure 36: Flow Pattern state for the new mud in Mk-X3 St-1

In Figure 36 could be seen the comparison of the flow pattern states for the original mud, the new mud and the new mud in safety state. The values for these states are described in the Table 28.

Table 28: Mud parameters for the redesigned and the original mud in Mk-X3 St-1

	Original Mud	**New Mud**	**New Mud in Safety Mode**
Flow rate (l/min)	2105	2400	2100
Hole diameter (in)	8.5	8.5	8.5
Pipe outside diameter (in)	5	5	5
Mud weight (s.g)	1.12	1.105	1.105
Plastic Viscosity (cP)	18	25	25
Yield Point (lb/100ft^2)	18	19	19
Cuttings Transport Ratio (%)	81	84	81
Flow Pattern	Laminar	Turbulent	Laminar
Differential Pressure @ 2578m (bar)	19.53	21.36	16.24
Differential Pressure in Sticking Situation (bar)	8.18	3.75	3.75

When the sticking occurred, there was no BHA in the well, in the classic terminology. There was PCL logging, so the logging tool and drillpipes were in the well.

Two centrifuges ran while drilling, so solids control could be considered as adequate. As generic mud type, polymer water-based mud was used. Fluid loss did not occur.

The acceptable changes on the sticking situation in the model could be seen in Table 29.

Table 29: Changes made on neural network model at sticking situation in Mk-X3 St-1

	Original	**Recommendation**
Measured Depth @ bit [m]	2578.3	2563
Inclination angle [°]	48.25	47
Dogleg Rate [°/30m]	0.56	0
Mud Weight [s.g.]	1.12964	1.105
Plastic Viscosity [cP]	17	25
Yield Point [lb/100ft^2]	17	19
Differential Pressure [bar]	8.18	3.75
Mud Weight @ drilling [s.g.]	1.12	1.105
Plastic Viscosity @ drilling [cP]	18	25
Yield Point @ drilling [lb/100ft^2]	18	19
Differential Pressure @ drilling [bar]	19.53	21.36

Although, the number of the changes was less than the previous well, TUS-80, the result was same, the situation was predicted as non-sticking by the neural network model, with 88.48% chance.

6.4.3 Ve-220

In this well, there is one straightforward cause of sticking. When the well was drilled, the mud weight was raised from 1.07 s.g. to 1.09 s.g. With the heavier mud, fluid loss occurred, but the well drilled successfully to the projected TVD. But after reaming the during the next POOH, they observed increased level in trip tank, closed the well. There was no return, when they tried to start circulation. After the decision was made of to continue the POOH, the string was stucked. This is a strange situation, when the mud weight was too light and too heavy at the same time. Too light, because there was a kick from the bottom, and too heavy, because differential sticking and fluid loss occurred above.

To solve this vicious circle, the main task is to check the casing settings, and if it could not be solved with the original number of casing sections, we need an extra casing string.

When investigating the calculated pore pressures, it could be found that there is a depleted, or naturally low pressure layer around 460 m, exactly where the sticking occurred. From that fact, it is clearly seen that the cause of the sticking is the too high differential pressure. In the next Figure the mud weight window has shown with the used mud weights.

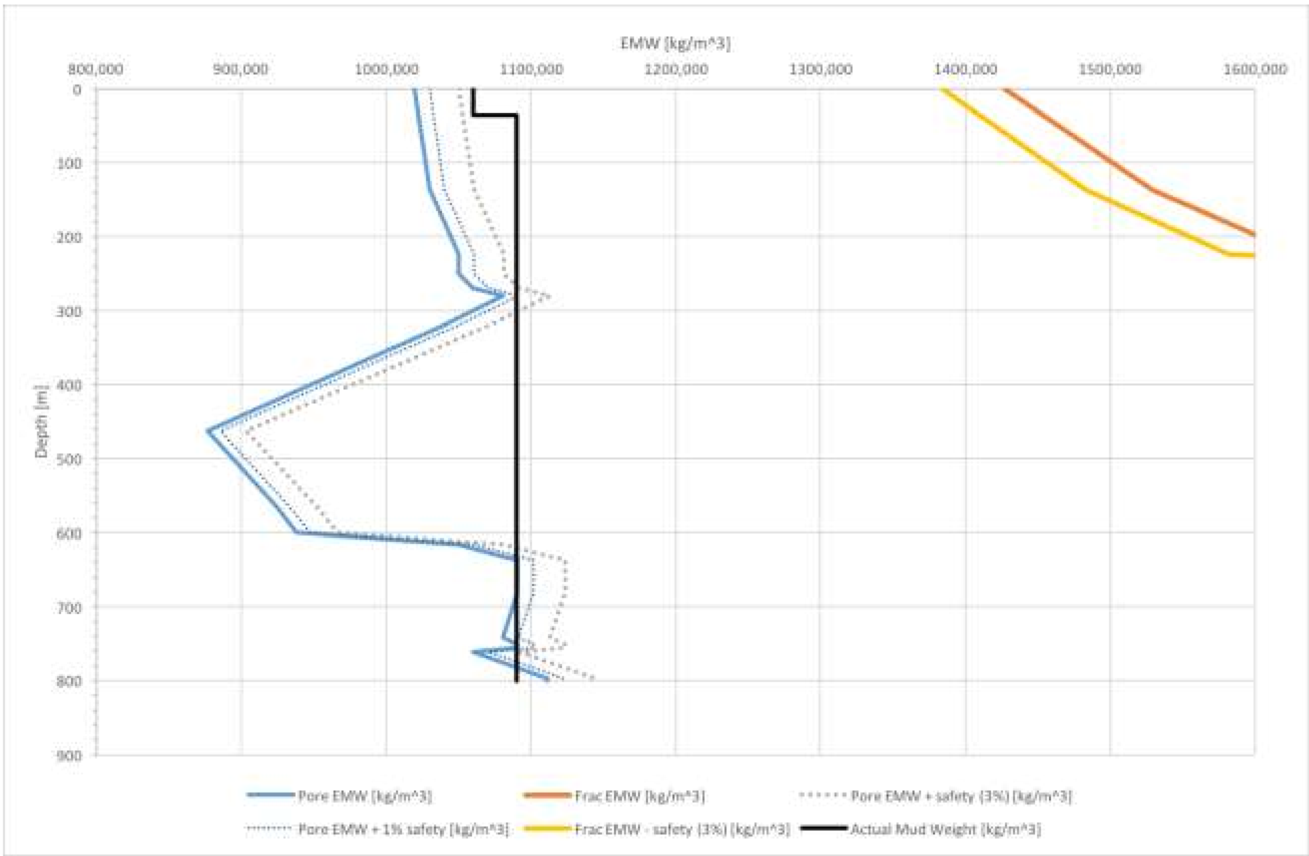

Figure 37: Mud Window in Ve-220 with used mud weights

As the Figure 37 shows, the used mud could not handle the pore pressure at the bottom of the well, however, it causes a very big, 9 bar differential pressure in static conditions.

Unfortunately, there are normal pressure layers above the low-pressure zone, so changing the casing seat depth would not solve the problem. To handle this problem, an extra casing section was used. The chosen mud weight, and casing setting depths could be seen in the following Figure and Table.

Table 30: Redesigned and Original Casing Section Data in Ve-220

	Original		New	
	Casing Seat TVD (m)	**Mud Weight (kg/m^3)**	**Casing Seat TVD (m)**	**Mud Weight (kg/m^3)**
Conductor	35	1060	35	1060
Surface	245	1090	365	1085
Intermediate	-	-	600	1000
Production	800	1090	800	1140

Conventional 3% safety margin was used in the bottom section of the well, and a riskier 1% in the differential sticking zone, to avoid sticking.

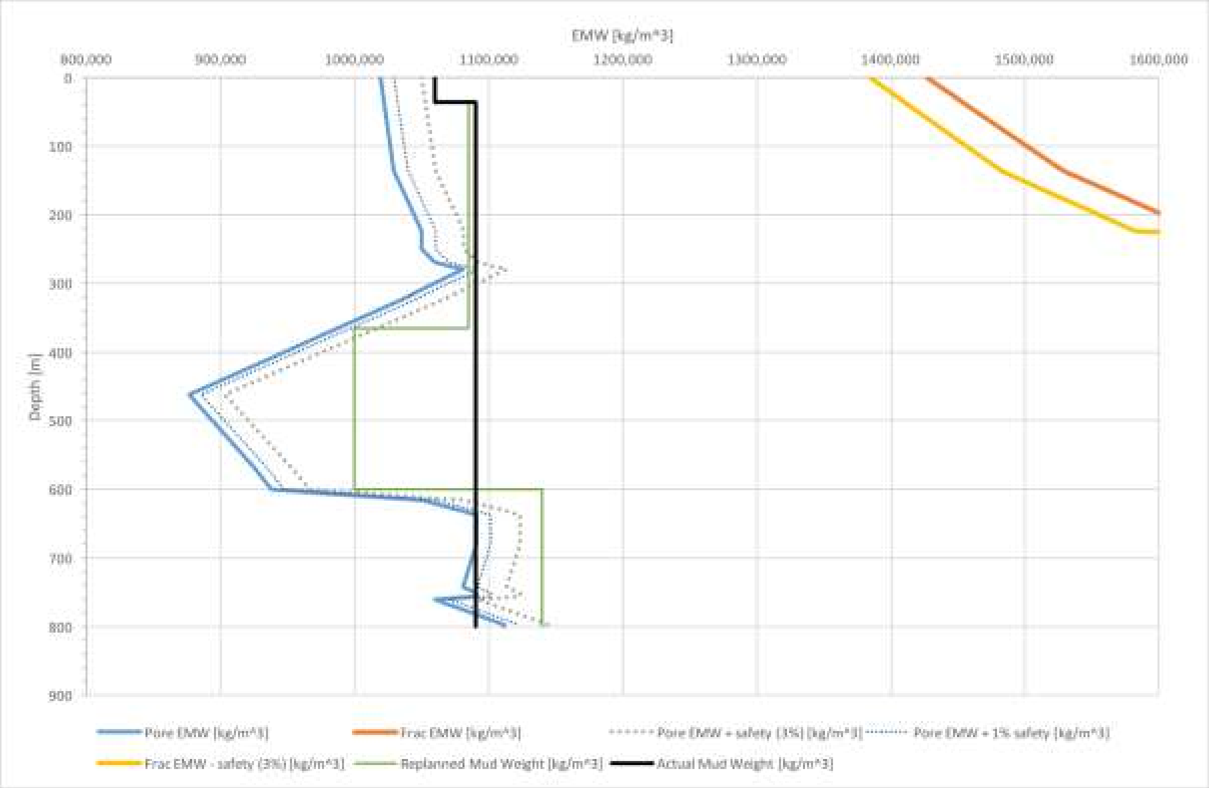

Figure 38: Mud Window in Ve-220 with new mud weights and casing seats

In the original plan the build-up section starts after the first casing shoe, so if the redesign would like to keep this proviso, the well trajectory had to recalculated for the new, lower casing shoe.

The max build-up angle was set to reach the tangent section at 600 m TVD, where the next casing shoe would have placed. Figure 39 shows the new trajectory design compared to the original well.

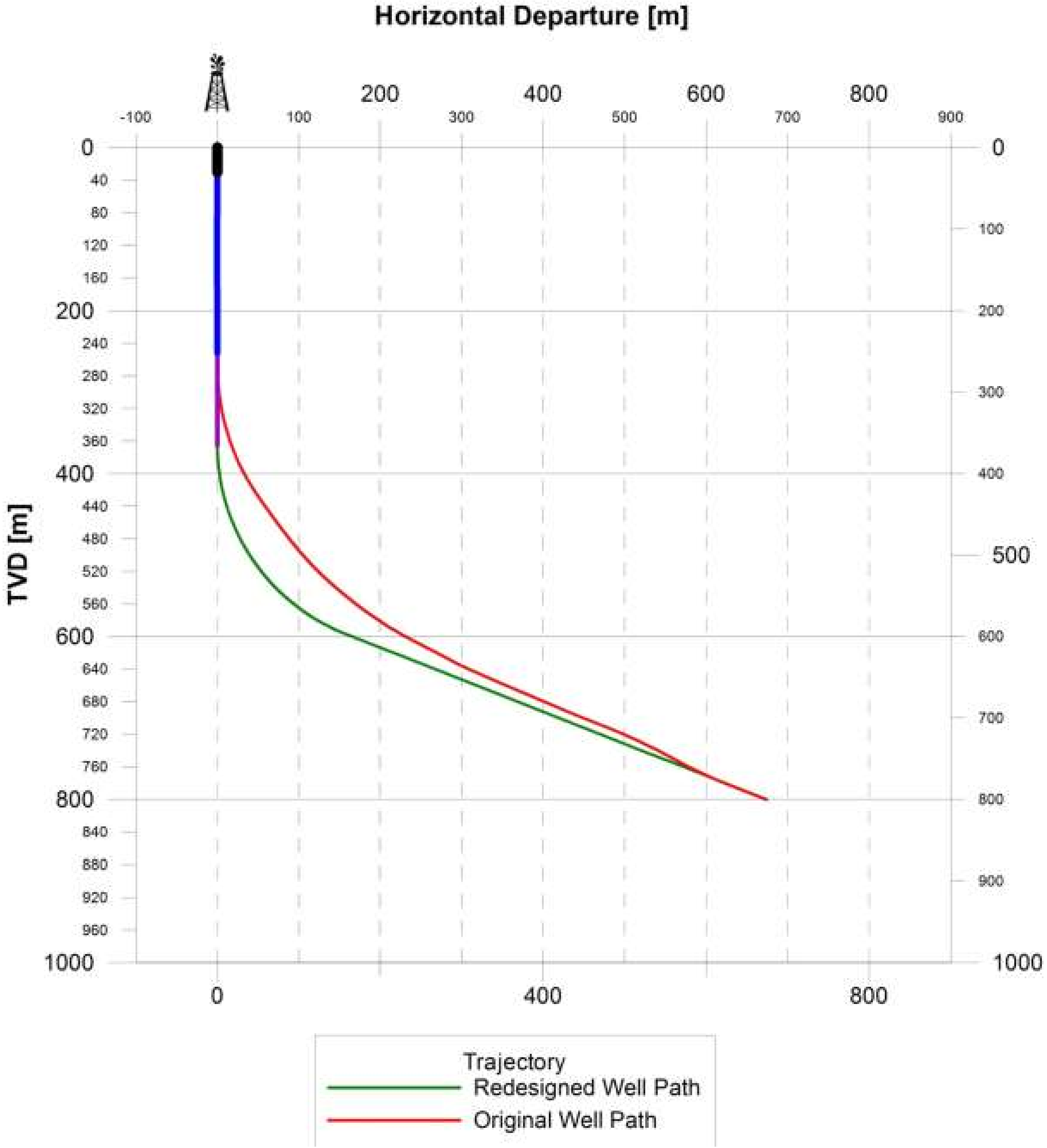

Figure 39: Redesigned and Original Well Path for Ve-220 well

The goal was to have the same 5 ½” production casing string. It could be found that if low clearance would be used, 5 ½” production casing string manageable with the original 9 5/8” surface casing. Table 31 contains the details of the new casing string.[1]

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[1] Calculation can be found in Appendix B.

Table 31: Casing properties for new casing design in Ve-220

	Size (in)	*Quality*	*Weight (lb/ft)*	*ID (in)*
Surface	9 5/8	K-55	40	8.835
Intermediate	7 5/8	H-40	24	7.025
Production	5 ½	J-55	14	5.012

The next step was to determine the flow conditions of the well. In the intermediate section, where the mud weight was chosen to be a very little, 1.0 s.g. and it is a fluid-loss risky zone, the flow designed for the achievable highest cuttings transport ratio, with the lowest differential pressure and laminar flow pattern. In the production casing section, where no danger of fluid loss, but what is a relatively high-inclination section, the author designed for turbulent flow.

In the intermediate section 96% cuttings transport ratio could be reached while the differential pressure kept below 6 bar. The cuttings considered as sandstone with 0.1” diameter and 16.66 ppg density. In the production casing section, the high mud weight was used, and turbulent flow could be reached with the properties in Table 32. In this section, the used 5” drillpipes have to change 3” ones, because using 5” drillpipes in 6.5” hole could cause problems. 84% transport ratio reached with considered limy dolomite cuttings as 0.5” diameter and 22.4 ppg density.

Table 32: Flow properties in the redesigned two casing section in Ve-220

	Intermediate section	**Production section**
Mud Weight (s.g)	1.0	1.14
Casing ID (in)	8.835	7.025
Hole ID (in)	8.5	6.5
Pipe OD (in)	5	3
Plastic Viscosity (cP)	15	20
Yield Strength (lb/100ft^2)	13	20
Flow Rate (l/min)	1500	2000
Differential Pressure (bar)	5.5	15.2
Transport Ratio (%)	96	84
Flow Pattern (-)	Laminar	Turbulent

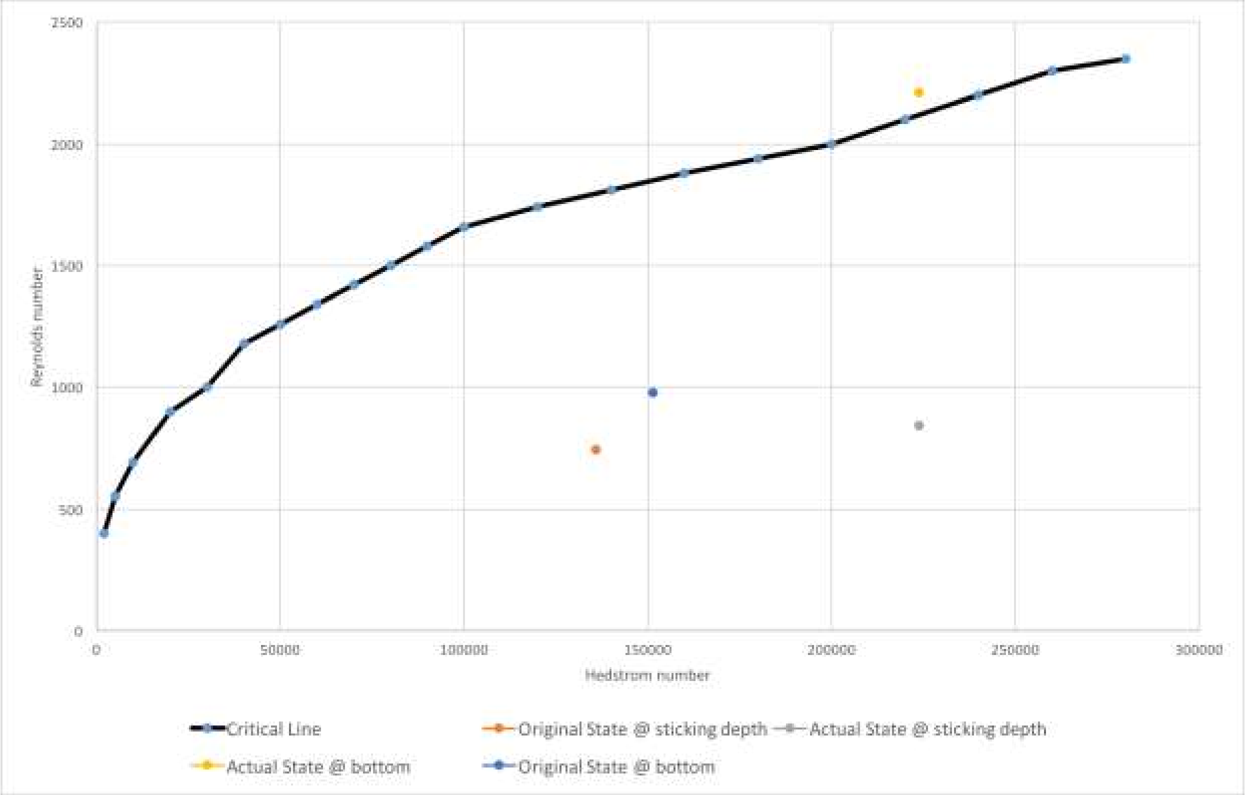


Figure 40: Comparison of Flow Patterns in Ve-220 for the original and redesigned states

By investigating the other influencing parameters of differential sticking, the author found that the responsible factor was the high differential pressure. When the sticking occurred, the BHA was made up with DCs, but the sticking occurred much above the BHA. Solids control equipment with running centrifuge was adequate, also the polymer-based mud was. The other parameters, like well trajectory and flow pattern were discussed above, because these also important for lowering the differential pressure.

With the applied modifications on the model, what could be seen in Table 33, the model predicted the situation as non-sticking with 88.48% chance.

Table 33: Changes made on neural network model at sticking situation in Ve-220

	Original	**Recommendation**
Measured Depth @ sticking [m]	440	428.56
Measured Depth @ bottom [m]	1177	1217.2
Inclination angle @ sticking [°]	33.32	14.388
Dogleg Rate [°/30m]	4.76	15.6
Open Hole Length [m]	932	548
Mud Weight [s.g.]	1.0754	1.14
Plastic Viscosity [cP]	16	20
Yield Point [lb/100ft^2]	16	20
Differential Pressure [bar]	10.66	Cased Hole
Mud Weight @ drilling [s.g.]	1.079	1.0
Plastic Viscosity @ drilling [cP]	20	15
Yield Point @ drilling [lb/100ft^2]	20	13
Differential Pressure @ drilling [bar]	9.61	5.5

7 Results & Conclusions

7.1 Results

The neural network model predicted all three generated datasets as non-sticking situation. On the other side, a prediction was made with the model for the original sticking situations, for checking the model. The exact results presented in the Table 34.

Table 34: Result of the neural network modeling

WELL	DATASET	DESIRED RESULT	ACTUAL RESULT	PREDICTION%
TUS-80	Original	Sticking	Sticking	99.86
TUS-80	Redesigned	Non-sticking	Non-sticking	88.48
Mk-X3 St-1	Original	Sticking	Sticking	100
Mk-X3 St-1	Redesigned	Non-sticking	Non-sticking	88.48
Ve-220	Original	Sticking	Sticking	100
Ve-220	Redesigned	Non-sticking	Non-sticking	88.48

While the accepted modifications were right, and the situations were non-sticking, the causes of each sticking situation could be stated.

Table 35: Causes of sticking

	Main cause	*Additional cause(s)*
TUS-80	High differential pressure	Improper hole cleaning, fluid loss, too many DCs
Mk-X3 St-1	Improper hole cleaning, thick mudcake	High differential pressure, long static time
Ve-220	High differential pressure	Fluid loss

In TUS-80 well, many of the known influencing parameter played a role. The main cause was the high differential pressure, because of the high mud weight. As additional, improper hole cleaning, too many DCs in the BHA and fluid loss problem also helped to get stucked. When these factors were managed, the situation was no longer predicted as non-sticking.

Applied modifications in TUS-80:

- The well trajectory was recalculated, so the inclination angle and the length of section in the problematic formation became lower.
- Checked and lowered the mud weight.
- Recommendation for changing blocking solid and switch to turbulent flow pattern stated.
- Decreasing the number of DCs could be done in the operation where the problem occurred.

In Mk-X3 St-1 well, the biggest problem was the too thick caused by the improper hole cleaning. It could be handled with adequate flow regime in the wellbore. Furthermore, the mud weight was also too high, what could be also lowered.

Applied modifications in Mk-X3 St-1:

- The mud weight and well trajectory were also revised.
- Hole cleaning improvement with cuttings transport ratio.

In Ve-220 the reason of the sticking was clearly the high differential pressure. Strangely enough, the same mud weight was too low to handle the pore pressure at the bottom of the well. The only solution in this situation was to put an extra casing string to the well.

Applied modifications in Ve-220:

- Extra casing section added.
- Recalculated trajectory and mud program.

Summarizing the results, the main reasons of differential sticking in this three wells were the too high mud weight, inadequate hole cleaning and fluid loss.

7.2 Conclusions

The initial presumption of a common reason was right under certain conditions. The mud weight was unnecessary high in all wells, as well as fluid-loss problems occurred, while there were hole cleaning problems also.

This study is also a proof of the importance of knowing the exact pore pressures. If the company would know the pore pressures prior to drilling in Ve-220 well, the sticking could have been avoided. In the other two cases, using the proper mud weight could also help to avoid sticking.

With real-time calculations, pore pressures could be determined also, thus last-time preventive actions could be taken. For this, method by Rehm and McClendon could be used.

Flow rate could be modified real-time, and it is influencing the differential pressure, flow pattern and transport ratio in one factor. Therefore, using the proper flow rate is crucial.

Fluid loss is also an influencing factor. If there is fluid loss, the mudcake would be undesirable thick, and the chance of sticking is increasing with the extent of fluid loss.

There are the same results of improper hole cleaning. If the drilled cuttings stay in the bottom of the hole, later they would build-in the mudcake, and it would be thicker.

In summary, the most important factors to avoid differential sticking:

- Knowing the pore pressures, thus applying enough casing string
- Carefully planned mud program
- Avoiding fluid loss
- Adequate hole cleaning

Recommendations for future drilling works are the following, based on the analysis, what described in this thesis:

- Closer cooperation between drilling and reservoir department to assume more accurate pore pressures during the planning phase
- Minimize overbalance
- Minimize the number of drill collars
- Prepare to handle fluid-loss with storing different sized loss circulation additives
- Adjust flow rate to achieve greater cuttings transport ratio
- Carefully planned casing string and casing shoe depths

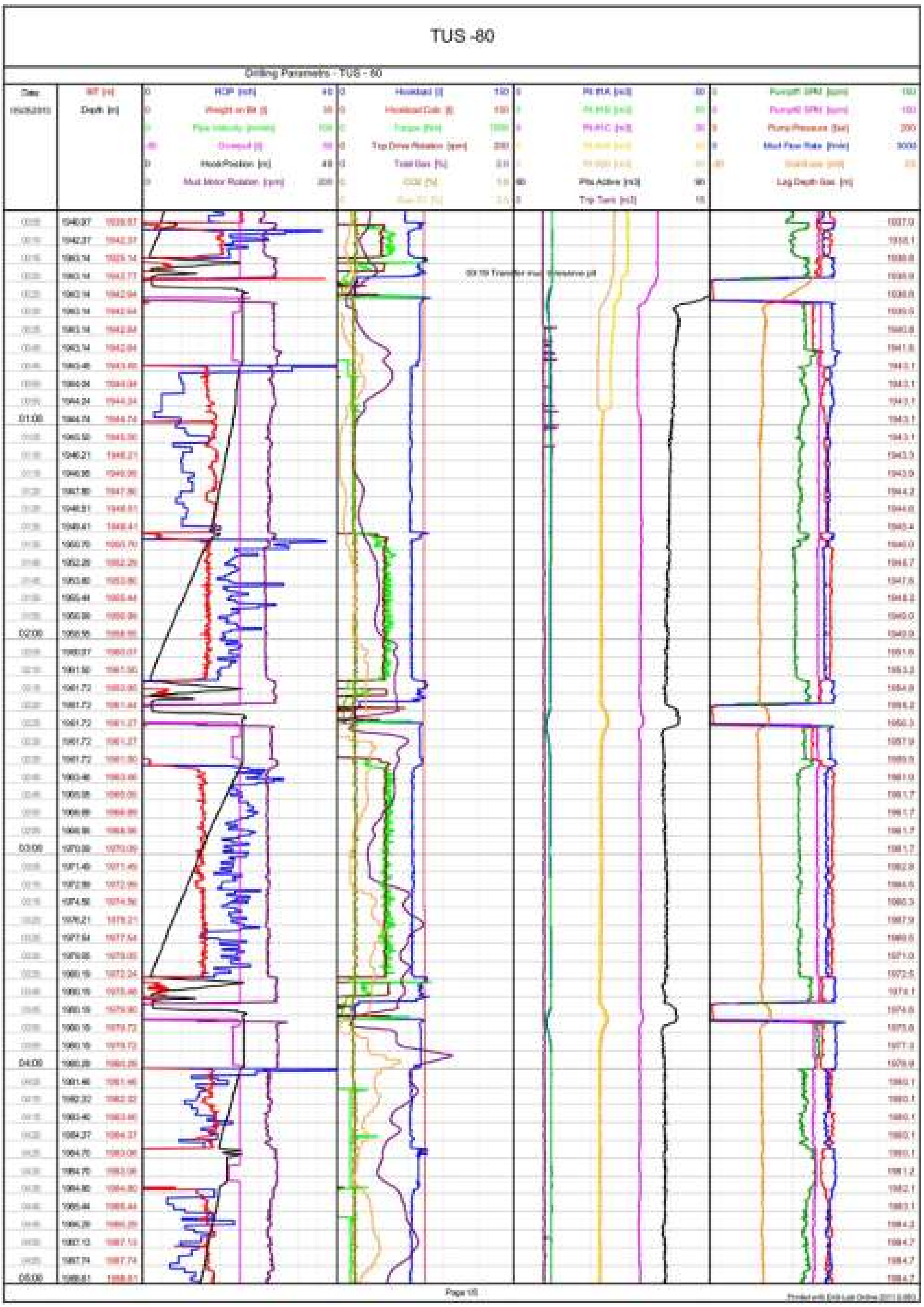
The author believes in that the recommended practices could help to avoid differential sticking situations in the future, which is proven by the result of the analysis combined with the neural network modeling.

Appendices

Appendix A

As it was described in chapter 5, the time-based logs from TUS-80 well came in pdf form, so it had to be digitalized somehow. The method was the following:

1. Original data sample splitted into single pages:

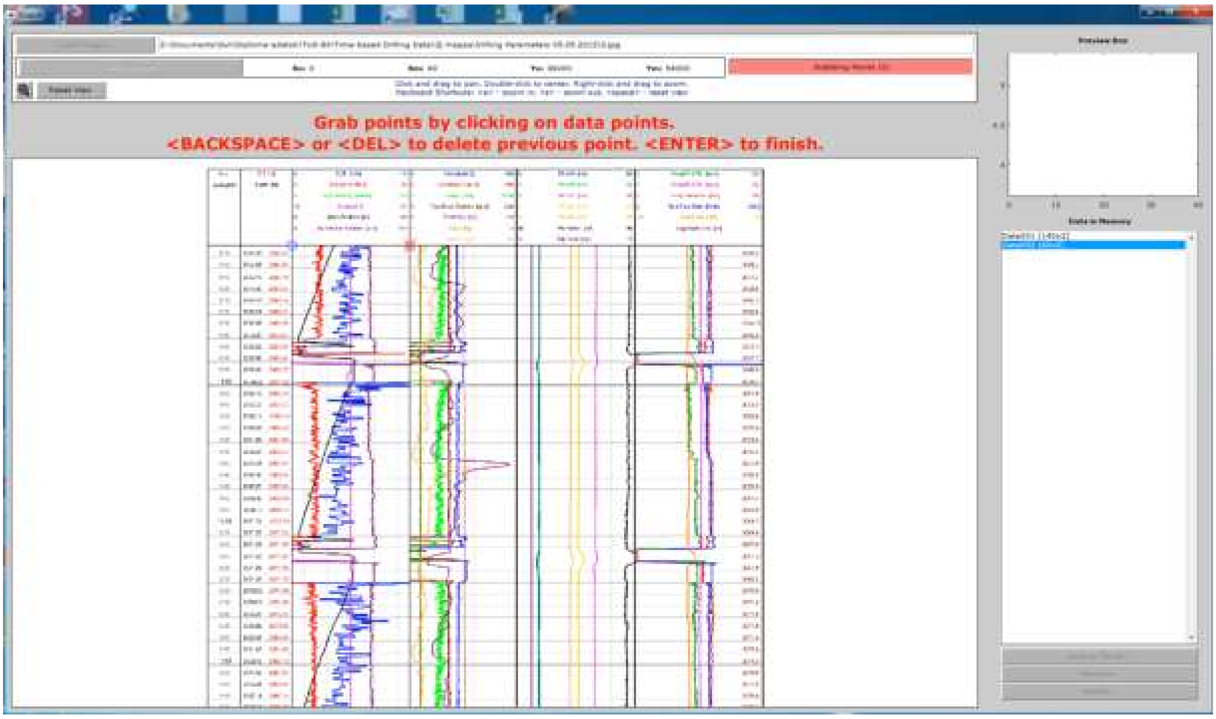


TUS -80

Drilling Parameters - TUS - 80

Figure 41: Original time-based data log from TUS-80 well (05.05.2013)

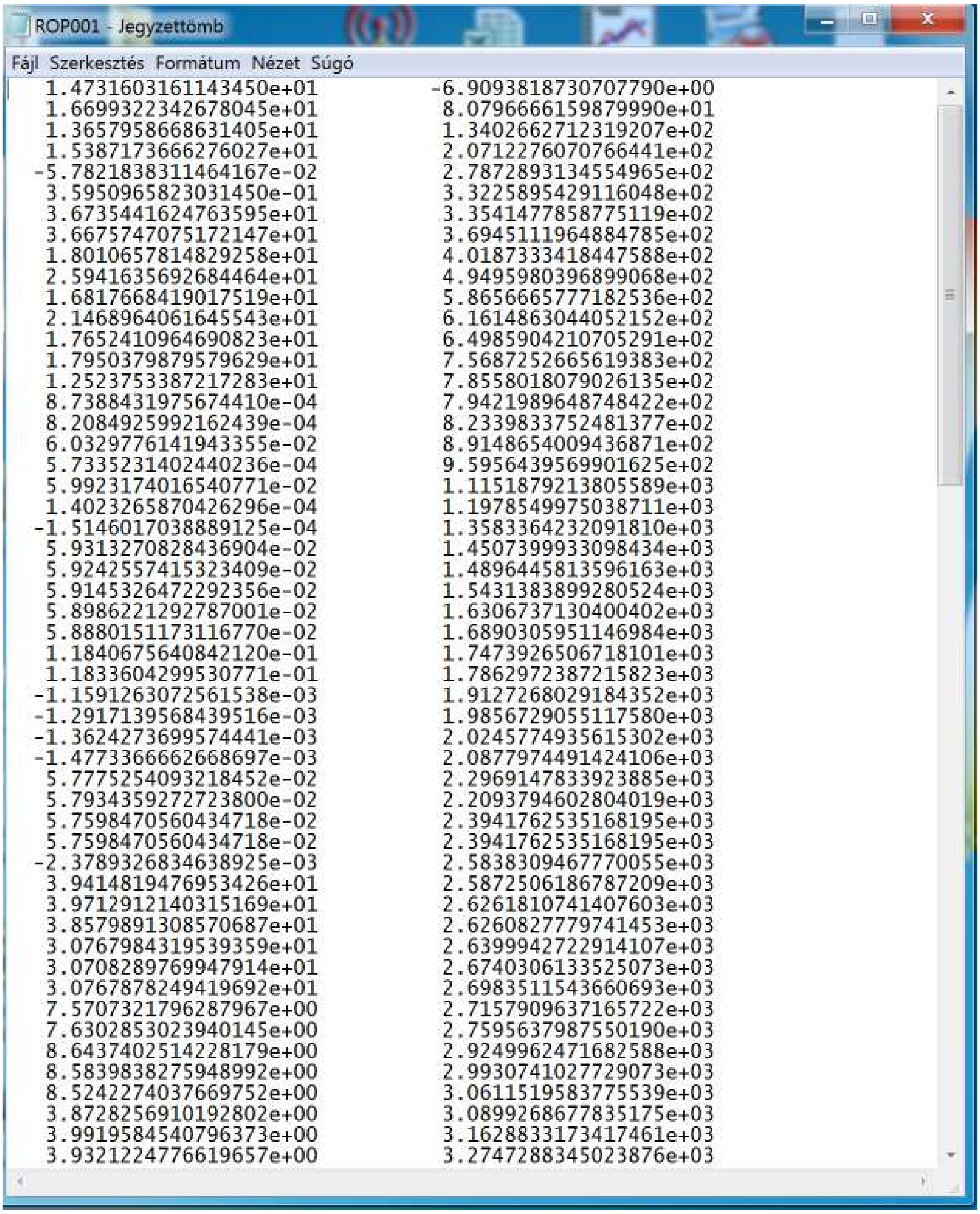
2. Use Mathlab software with Grabit plugin, which is capable to digitalize graphs:



Grab points by clicking on data points.
<BACKSPACE> or <DEL> to delete previous point. <ENTER> to finish.

There are numerous software on market which is capable to digitalize graph, someone even automatically, but in this case, because it is a really difficult graph what has many crossovers, the digitalization had to be done manually. It is not a 100% punctual method, but we are (and neural network model tools) looking for trends. The data was digitalized from 05.05.2013 and 06.05.2013 while the problematic zone was drilled, basically data was collected from every 5 min, between 2150m and 2180 m MD, 3 data points from every 5 minutes. Another data set from wiper trip RIH after drilling, and the maybe the most important, from the wiper trip after logging, when the sticking had occurred and while the drillstring was stuck and freed. (From 09.05.2013 2:50-12:00 5 datapoints from every 5 min, after that one point per 5 min, from 10.05.2013 6:00-10:00 1 point per minutes.)

3. To obtained data is at the the following form in txt file:



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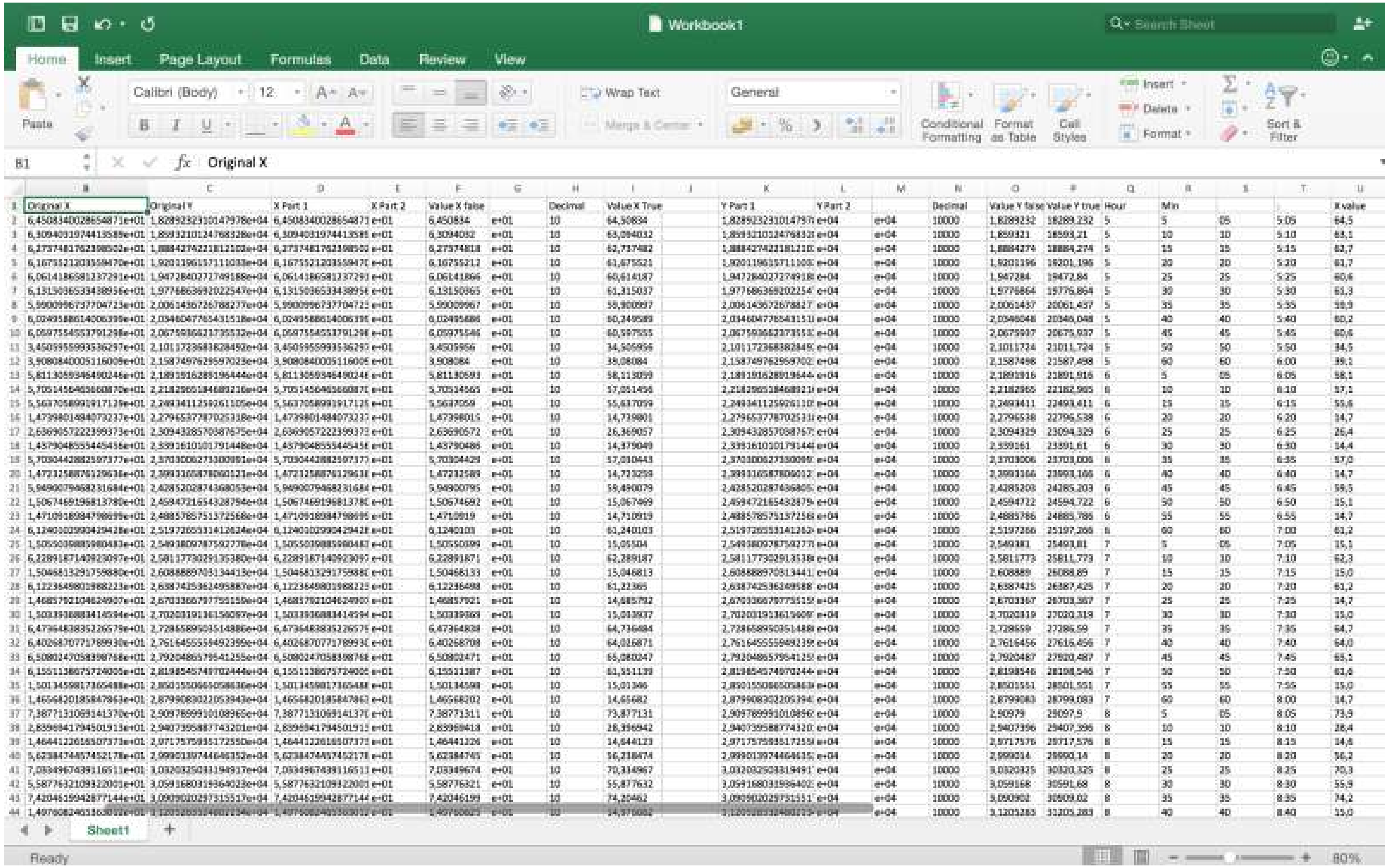
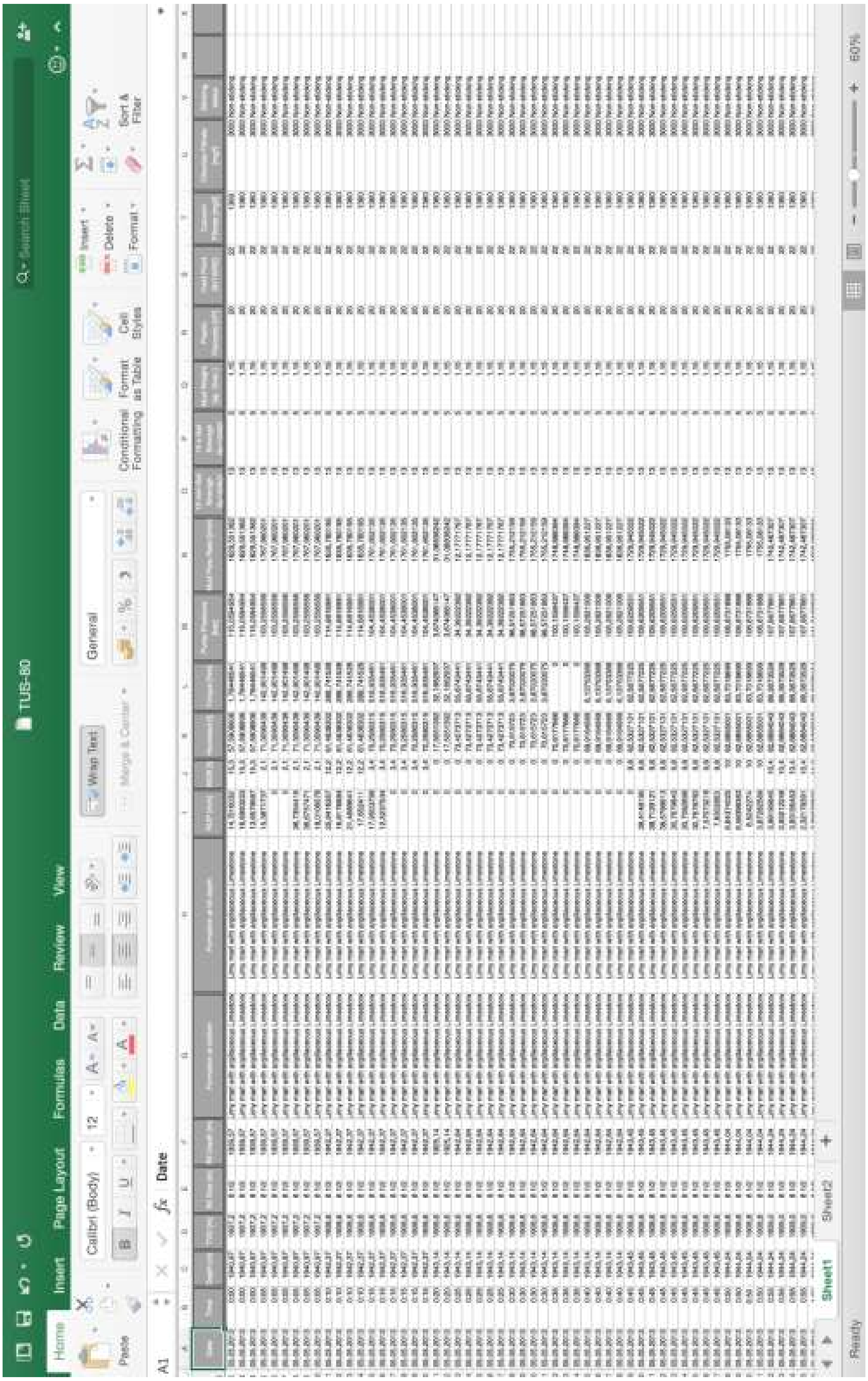
   1.5387173666276027e+01           2.0712276070766441e+02
  -5.7821838311464167e-02           2.7872893134554965e+02
   3.5950965823031450e-01           3.3225895429116048e+02
   3.6735441624763595e+01           3.3541477858775119e+02
   3.6675747075172147e+01           3.6945111964884785e+02
   1.8010657814829258e+01           4.0187333418447588e+02
   2.5941635692684464e+01           4.9495980396899068e+02
   1.6817668419017519e+01           5.8656665777182536e+02
   2.1468964061645543e+01           6.1614863044052152e+02
   1.7652410964690823e+01           6.4985904210705291e+02
   1.7950379879579629e+01           7.5687252665619383e+02
   1.2523753387217283e+01           7.8558018079026135e+02
   8.7388431975674410e-04           7.9421989648748422e+02
   8.2084925992162439e-04           8.2339833752481377e+02
   6.0329776141943355e-02           8.9148654009436871e+02
   5.7335231402440236e-04           9.5956439569901625e+02
   5.9923174016540771e-02           1.1151879213805589e+03
   1.4023265870426296e-04           1.1978549975038711e+03
  -1.5146017038889125e-04           1.3583364232091810e+03
   5.9313270828436904e-02           1.4507399933098434e+03
   5.9242557415323409e-02           1.4896445813596163e+03
   5.9145326472292356e-02           1.5431383899280524e+03
   5.8986221292787001e-02           1.6306737130400402e+03
   5.8880151173116770e-02           1.6890305951146984e+03
   1.1840675640842120e-01           1.7473926506718101e+03
   1.1833604299530771e-01           1.7862972387215823e+03
  -1.1591263072561538e-03           1.9127268029184352e+03
  -1.2917139568439516e-03           1.9856729055117580e+03
  -1.3624273699574441e-03           2.0245774935615302e+03
  -1.4773366662668697e-03           2.0877974491424106e+03
   5.7775254093218452e-02           2.2969147833923885e+03
   5.7934359272723800e-02           2.2093794602804019e+03
   5.7598470560434718e-02           2.3941762535168195e+03
   5.7598470560434718e-02           2.3941762535168195e+03
  -2.3789326834638925e-03           2.5838309467770055e+03
   3.9414819476953426e+01           2.5872506186787209e+03
   3.9712912140315169e+01           2.6261810741407603e+03
   3.8579891308570687e+01           2.6260827779741453e+03
   3.0767984319539359e+01           2.6399942722914107e+03
   3.0708289769947914e+01           2.6740306133525073e+03
   3.0767878249419692e+01           2.6983511543660693e+03
   7.5707321796287967e+00           2.7157909637165722e+03
   7.6302853023940145e+00           2.7595637987550190e+03
   8.6437402514228179e+00           2.9249962471682588e+03
   8.5839838275948992e+00           2.9930741027729073e+03
   8.5242274037669752e+00           3.0611519583775539e+03
   3.8728256910192802e+00           3.0899268677835175e+03
   3.9919584540796373e+00           3.1628833173417461e+03
   3.9321224776619657e+00           3.2747288345023876e+03
```

Unfortunately, Microsoft Excel’s text importer could not import this data in proper from, so it had to converted.

4. With an Excel function the author had to convert the data from text format to numerical format (using the left, right, if, concatenate, value, round functions), and the data had to sorted by time:



5. With extended the obtained data with other data what got from the reports, the final database was ready:



With this method 10488 points was captured, what extended with mud properties and depth data, finally 1748 database was created.

Appendix B

Well Trajectory

The well trajectory was calculated with the method described by Bourgoyne et al.[1]

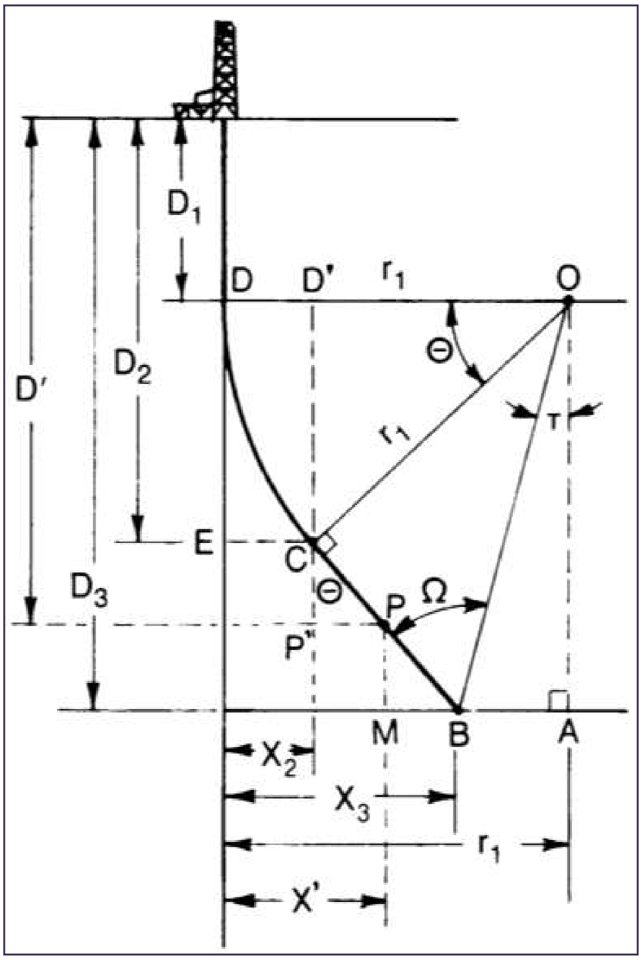


Figure 42: Geometry of build-and-hold type well path[1]

For this calculation, we need the target TVD (*D_3*), the horizontal departure (*X_3*), KOP (*D_1*) and the build-up rate (*q*). In this case, all of these were known.

First step is to calculate the radius of curvature, *r_1:*

$$r_1 = \frac{180}{\pi} * \frac{1}{q}$$

The maximum inclination angle, θ is:

$$\theta = \Omega - \tau$$

---

[1] Bourgoyne A. T., Millheim K.K., Chenevert M. E., Young Jr. F.S. 1986. “Applied Drilling Engineering”. Richardson, Texas, USA: Textbook Series, SPE.

where

$$\tau = \tan^{-1}\frac{r_1 - X_3}{D_3 - D_1}$$

and

$$\Omega = \sin^{-1}\left[\frac{r_1}{\sqrt{(r_1 - X_3)^2 + (D_3 - D_1)^2}}\right]$$

The length of the arc, in the Figure DC:

$$L_{DC} = \frac{\theta}{q}$$

The length of tangent section, CB:

$$L_{CB} = \frac{r_1}{\tan\Omega}$$

The total measured depth:

$$D_M = D_1 + \frac{\theta}{q} + \frac{r_1}{\tan\Omega}$$

For any P point, the measured depth can be calculated by:

$$D_{MP} = D_1 + \frac{\theta}{q} + \frac{D' - D_1 - r_1\sin\theta}{\cos\theta}$$

where D' is the TVD of the point.

Horizontal departure of this P point is:

$$X' = r_1(1 - \cos\theta) + (D' - D_1 - r_1\sin\theta)\tan\theta$$

Pore Pressure Gradient

Pore pressure gradient determination was done by using the modified d-exponent in Rehm and McClendon's equation for pore gradient.

The first step in determination is the d-exponent calculation:

$$d_{exp} = \frac{\log\left(\frac{ROP\,[ft/hr]}{60 * RPM[min^{-1}]}\right)}{\log\left(\frac{12 * WOB[lbf * 1000]}{1000 * d_{bit}[in]}\right)}$$

Modified d-exponent for accounting the overbalance:

$$d_{mod} = d_{exp}\frac{\rho_n}{\rho_e}$$

where ρ_n is the equivalent mud density of normal pore pressure, considered as 0.1 bar/m, and ρ_e is the ECD at bit.

Final step is Rehm and McClendon equation for pore gradient:

$$g_p = 7.65 * \log[(d_{mod})_n - (d_{mod})] + 16.5$$

Casing Design

In casing selection, design based on three factors: burst, collapse and tension. Every parameter determined with worst case scenario. It means the following:

1. Hydraulic pressure of the mud as collapse pressure

$$p_{collapse}(bar) = \rho_{mud}\left(\frac{kg}{m^3}\right) * g * TVD(m) * 10^{-5}$$

2. Formation fracture pressure as burst

$$p_{burst}(bar) = EMW_{frac}\left(\frac{kg}{m^3}\right) * g * TVD(m) * 10^{-5}$$

3. Casing string weight in air for tension

$$F_{tension} = Nominal\ Weight\ \left(\frac{kg}{m}\right) * MD\ (m)$$

Very great design factors were used. For collapse 2, for burst 1,5 and for tension 3. To get actual safety factors, we had to divide the nominal resistance values of the selected casing with the given values. The selected casing string for Ve-220 well was highly fulfilled these designing factors.

Cuttings Transport Ratio

To calculate the transport ratio, the Chien's correlation was used to determine the slip velocity. It is valid if the Reynolds number is less than 100. And for Chein's equation, the apparent viscosity is also necessary.

Apparent viscosity:

$$\mu_a = \mu + \frac{5\tau_y\left(D_h - D_{op}\right)}{\bar{v}}$$

τ_y is the yield point (lb/100ft^2), D_h is the hole diameter (in) (in cased hole, the inner diameter of the casing, in open hole the diameter of the bit), D_p is the outer diameter of the drillpipe, and μ is the plastic viscosity and $\bar{v}$ is the annular velocity.

Slip velocity:

$$\bar{v}_{sl} = 0.0075 * \left(\frac{\mu_a}{\rho_f d_s}\right) * \left[\sqrt{\frac{36800 * d_s}{\left(\frac{\mu_a}{\rho_f d_s}\right)^2} * \left(\frac{\rho_s - \rho_f}{\rho_f}\right) + 1} - 1\right]$$

where $\bar{v}_{sl}$ is the slip velocity (ft/s), μ_a is the apparent viscosity (cP), ρ_f is the fluid density (ppg), ρ_s is the solid density (ppg) and d_s is the slip diameter (in).

Reynolds number for cuttings:

$$N_{Re} = \frac{928\rho_f \bar{v}_{sl} d_s}{\mu_a}$$

Transport ratio:

$$F_T = 1 - \frac{\bar{v}_{sl}}{\bar{v}_a}$$