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Extended Reach Drilling with the example of Reelwell Drilling Method

"Influence examination of different drill pipes on drilling performance on Idun field on the Norwegian Continental Shelf by PGNiG Norway AS."

A thesis

by

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I Abstract

Horizontal or extended reach drilling is incredibly fast growing technology. Although in some areas of the world ERD is still novelty, most of oil companies have been using the technology reliably and successfully for dozens of years. And those companies want to improve well-worn solutions to obtain better performance, thereby reducing costs.
One of the main aspects that affects drilling performance and efficiency is adequate choice of drill pipes.

The paper describes way of drill pipes' selection that is based on detailed analyses and calculations of such factors as:

a) fatigue resistance & wear phenomenon

b) drag & torque issues

c) torsion strength, buckling tendencies

d) BHA design

For each of the factors shown above, appropriate analyze model has been chosen to simplify the train. Moreover all of the calculations required were presented and explained in accessible way. Additional comments were run where needed.

Further, three different drill pipes have been selected to show possible ways of improvement. They differ with material (S-135 steel DP, Aluminum DP, Composite DP), with size (4 ½", 5", 5 ½" for steel and aluminum pipes, 3 $^{3/8}$", 5 ½" for composite pipes) as well as with different mechanical properties.

To cast light on technical feasibility, theoretical assumptions regarding wellbore design, wellbore and environmental conditions have been made. Data such as drill pattern, drill design, wellbore size(s), TVD, MD and temperature had to be assumed. They are specified, not to have them wrong, with the real data provided by Dolphin Drilling Company.

Furthermore, all of the results are briefly presented and detailed comparison has been made. The best solution, for the given wellbore conditions, has been chosen and shown with close comment and justification.

Finally, alternative solutions have been presented as well. Possibility of the results improvement with additional equipment has been explained.

II Dedication

The Master Thesis is dedicated to my parents for their support over the years of studying.

III Acknowledgments

First and foremost, I would like to thank Prof. Arnfinn Nergaard and Dr Robert Rado for support and help over the last months, while doing the thesis.
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VII Objectives

- preparation of a model well design with Schlumberger's 'Petrel' software
- theoretical assumptions regarding drill string
- qualification of productive & cost-effective drill pattern
- selection of the most adequate drill pipes for the given wellbore conditions
- selection of suitable models for given technical problems
- theoretical analyses & calculations regarding chosen models
- detailed comparison of results
- selection of best drill pipes' type
- research of efficient alternative solutions

1. Introduction

1.1 A brief history of drilling

The history of oil industry reaches thousands years back. In the beginning there was used really primitive equipment to reach depths around 800ft (240m). Then it developed to more advanced solutions and nowadays we are able to drill holes that are more than 12.000m (40.000ft) deep and even more.

The first known well was drilled in China around 347CE. It had depth around 800 ft (240m) and had been drilled with bits connected with bamboo poles. The produced oil was burned and used to evaporate brine and produce salt. Around 10th century extensive network of mentioned bamboo poles connected oil wells with salt springs.

Petroleum industry in the Middle East was started by Persian alchemist named Muhammad ibn Zakariya Razi, who was the first one that distilled oil, thereby producing paraffin, also known as kerosene. The chemical was used especially to be energy for lamps. However, some time after, Arab and Persian chemists distilled crude oil to produce flammable products for military purposes.

According to other sources, it is said that oil was discovered and exploited about 9th century around modern Baku (Azerbaijan) to produce naphtha for needs of oil industry. These fields were described in 13th century by Marco Polo, who characterized their amount as hundreds of shiploads.

In modern times, first wells were drilled with cable hammering. Soon after, the solution was replaced with rotary drilling systems, which allowed drilling much faster, reaching greater depths and to being much more efficient in general.

Just in 1859, in northwestern Pennsylvania, the most important well in history of The United States was drilled. It was one of the first wells in the country with confirmed presence of hydrocarbons. The well was named as ‘Drake Well’, after ‘Colonel’ Edwin Drake that was responsible for the discovery, which changed the way the world has been leaving with.

Then, about 1920s, some oilfields were established in such countries as Poland, Sweden, Canada, Ukraine, the United States of America, as well as in Venezuela.

In the early 1930s the Texas Company, now named Texaco, developed the first mobile steel barges to provide ability to drill offshore of the Persian Gulf.
In 1937 Pure Oil Company & Superior Oil Company (first is a member of Chevron Corporation and second one of ExxonMobil Corporation now), used fixed platform in 14 feet of water to drill offshore well in coastal region of Louisiana.|
Then, in early 1947 Superior Oil moved its drilling/production oil platform about 18 miles off Vermilion Parish (Louisiana) to area with 20 feet of water.
After World War II ended, Middle East countries, with Russia in the front, took a lead in oil production.

Already in 1970 the longest vertical well ever was drilled in Kola Peninsula (USSR) using non-rotary mud motor drilling achieving depth over 12.000m (39.000ft).

Until 1970 most of wells was vertical, at least in theory. Because of some lithological and mechanical issues, imperfections, the wells were slightly deviated from true vertical axis. Only modern directional drilling techniques introduced possibility to deviate a hole deliberately.

1.2 Overview of directional drilling

Directional drilling techniques evolved slowly from traditional vertical drilling. First real purpose of application of directional drilling was due to a “fish” – unrecoverable drilling tools lost in the hole. Directional methods allowed drilling around and bypassing tools that stayed in a well. The solution was much more cost efficient than drilling a new hole.

The whipstock was the first absolutely reliable tool used in directional drilling. The drilling was being developed pretty slow in compare to vertical drilling, however developments in measuring instruments made a huge step into direction of modern directional drilling developments.

Directional drilling, as a technique, is defined as procedure for drilling a non-vertical hole through the earth. For the first time it was used in south-east Texas while controlling blowout in the mid-1930s. A relief well was drilled in a safe distance from the broken well.

Its task was to reduce the pressure in the broken one and pump down the heavy fluid to control the blowout. The operation was successful and received widespread publicity. After the situation, attention was focused on somewhat called new drilling procedure.

Directional drilling had a strong start offshore or in geologically difficult areas, as well as in places where building a new construction was too expensive.
Directional techniques allowed drilling multiple wells from one location, thereby eliminating need of constructing an expensive structure for each well.

These and other procedures established directional drilling and developed it into reliable and efficient technique with wide spread of usage.

1.3 Extended Reach Drilling as an extreme version of directional drilling

While the oil industry was becoming mature, wells were vertically drilled to 30.000 ft or sometimes even deeper. However, very deep drilling was not cost-effective and was often indicating that oil & gas reservoirs were not placed at such depths.
These aspects led to Extended Reach Drilling – Directional Drilling to greater distances.

Soon after, horizontal drilling started to evolve, mainly to increase well productivity. It changed traditional vertical drilling to deviated or just horizontal one.

The first such wells had one or more short holes drilled horizontally into the formation from vertical wellbore, just to expose more and more of the reservoir, thereby producing larger volumes of oil & gas.

Then, horizontal wells started to have larger and larger horizontal length, thus decreasing vertical depth. As the example of such situation we can quote 'Extended Reach Well in Wytch Farm'.
The well was drilled in 2000 reaching just 1.500m of TVD, but more than 12.000m of MD.

Nowadays, the situation has been guiding into even shallower vertical depths but greater horizontal reaches. The greatest example can be Odoptu OP-11 well drilled by Parker Drilling for Exxon Neftegas on Sakhalin Island in Russia. The well reached a total MD of 12.345m, however a horizontal reach is equal to 11.475m.

Main problems of Extended Reach Wells are still the same: hole cleaning, Weight-On-Bit, drag & torque, buckling tendencies, pressure control as well as wellbore stability.
For the sake of increasing well patterns and wellbores complexity, even significant development of new technologies, didn't meaningfully level mentioned problems.

So, how to classify a given well as an extended reach one? In 1981, Extended Reach Well had MD of just 5.000ft. Nowadays, Extended Reach Wells reach 12.000ft of MD or even more. Moreover, with keeping the same technological progress, it is predicted to drill wells with 20km length or even deeper.

1.4 Recent developments

In this section of the thesis, three longest Extended Reach Wells will be depicted with some basic information about them.

First and foremost, last development of Exxon Neftegas in Sakhalin – Odoptu OP-11 well with 40.502ft of MD will be presented.

Further one, Maersk Oil Qatar well, drilled offshore in 2008, in Qatar, which has 40.320ft of MD will be described.

At the end, Wytch Farm development drilled for BP in United Kingdom in 2000 with MD of 34.967ft will be shown.

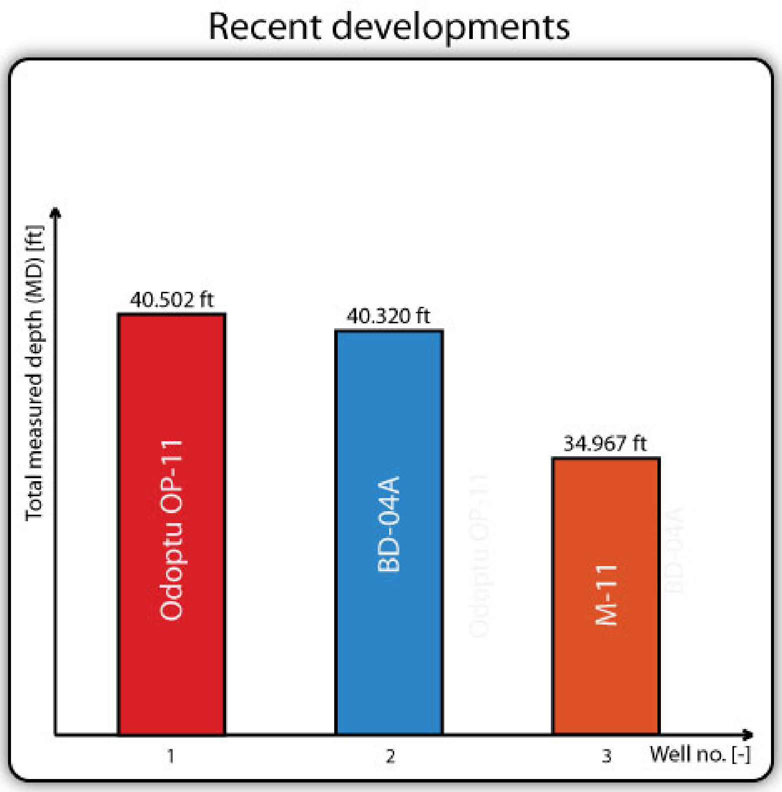


Fig. 1. Recent developments in Extended Reach Drilling

Odoptu OP-11 (Russia)

Exxon Neftegas Limited has drilled the longest extended reach well in the world. It has been done at Odoptu oil field, far east from Russia.

The total measured depth of the well (OP-11) is equal to 40.502ft (12.345m / 7,671 miles).

Also world record in horizontal reach has been beaten – 37.648ft (11.475m / 7,131 miles).

Moreover the whole drilling process has lasted just 60 days, thanks to ‘Exxon Mobil’s Fast Drill Process & Integrated Hole Quality process.

Since the time when the first well was drilled at Sakhalin-1 project in 2003, six of the world’s 10 record-setting ERD wells have been drilled at the project. It indicates how technologically advanced the development is.

BD-04A (Qatar)

The second longest Extended Reach Well was drilled by Maersk Oil Qatar in May 2008, offshore Qatar.

The total measured depth of the well (BD-04A) amounts to 40.320ft (12.290m / 7,637 miles). However, step-out equals 37.956ft (11.569m / 7,189 miles).

The original length of the well was designed to 28.850ft, but then it was extended to reach 40.320ft.

Besides the fact that the well is the second longest well in the world, it has broken some other world records, especially in longest well drilled with rotary steerable Bottom Hole Assembly and Logging-While-Drilling, highest reach vs. TVD ratio of 10,48, as well as highest directional difficulty index of 8,279.

M-11 (United Kingdom)

The last Extended Reach Well in the breakdown is, drilled by British Petroleum at Wytch Farm, M-11 well.

The total measured depth of the well is 34.967ft (10.658m / 6,623 miles). Horizontal displacement equals 33.182ft (10.114m / 6,285 miles).

M-11 well is the second extended-reach world breaking well at Wytch Farm. The first of them is named M-05, with measured depth of 28.593ft(8.715m / 5,416 miles) and with horizontal displacement of 26.361ft (8.035m / 4,993 miles). It is said that both wells owe their success to logging and measurements tools (‘Anadrill’), as well as ‘GeoSteering’ tools.

2. Skarv field

2.1 General overview of the field

2.1.1 Overview

Skarv/Idun field is located in the northern part of Norwegian Sea, at Sandnessjøen-level. It consists of two separated parts that are situated in water depths ranging from 1.148ft to 1.476ft (350m to 450m).

First of the fields – Skarv, was discovered in 1997. Then, 1 year later, Idun was found. Although huge potential of the fields was expected, they were not deemed commercially viable until next 10 years passed.

The fields contain hydrocarbons at three reservoir levels.

2.1.2 Skarv field

Precisely, Skarv field is located in North Sea, 77 miles (200km) on west from Brønneysund. Water depths range from 820ft – 1.476ft (250m – 450m). The field is placed at following blocks: 6507/5, 6507/6, 6507/3, 6507/2.

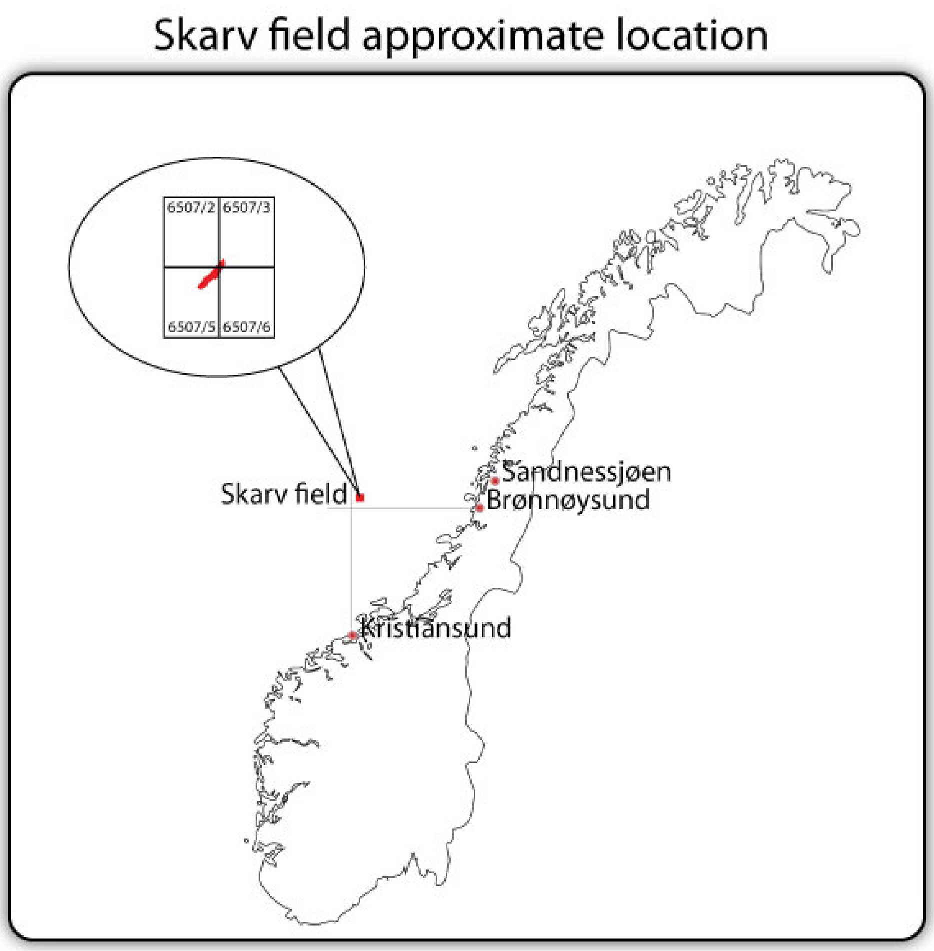


Fig. 2. Skarv field approximate location

Skarv was discovered on 24.12.1997 by Mærsk Jutlander semisubmersible unit. The very first well – 6507/5-1 – had reached 13.858ft (4.224m) depth.
In 2002, appraisal well, which reached 12.959ft (3.950m) depth and was drilled by West-Alpha semisubmersible unit, confirmed presence of gas condensate and oil.

At the field hydrocarbons mentioned above will be produced, with help of gas-injection. Originally the field was named 'Donatello', however after some time it was changed to 'Skarv'.

2.1.3 Idun field

Idun field is located exactly 124miles (200km) west from Brønnøysund. Water depths there, similarly to Skarv field, range from 1.148ft to 1.476ft (350m – 450m).
The field is placed on block 6507/3-3.

Idun field approximate location

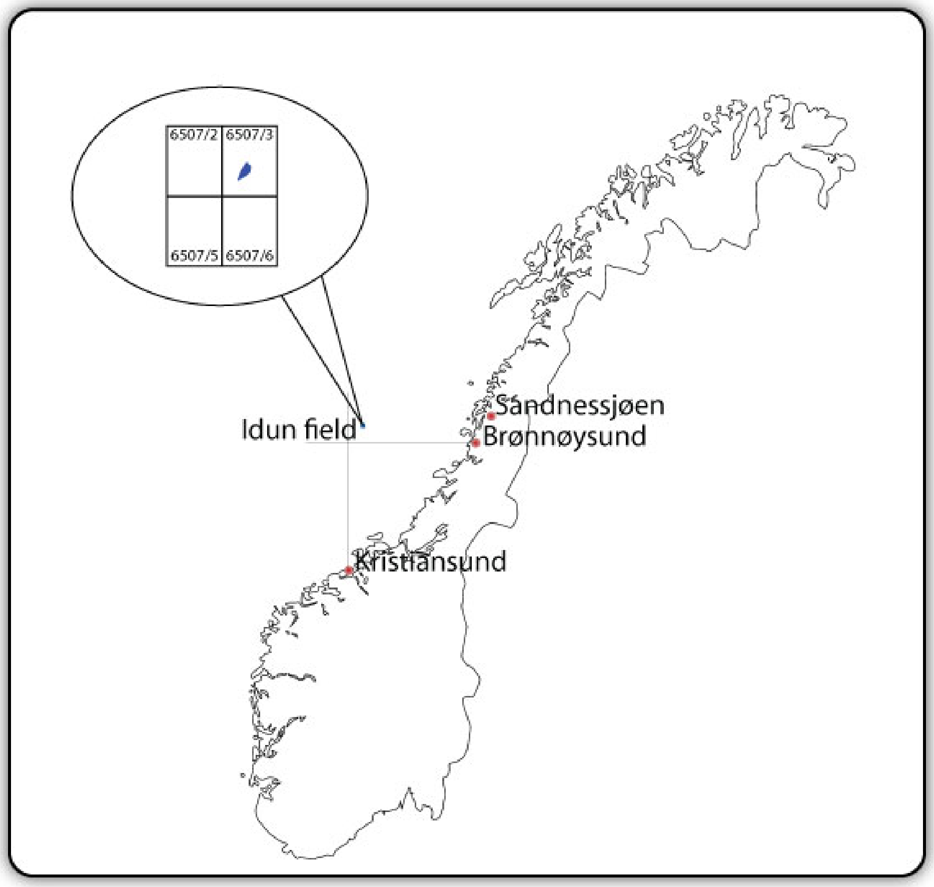


Fig. 3. Idun field approximate location

On 23.12.1998 first well was drilled – 6507/3-3 – by Byford Dolphin semisubmersible unit. It reached 12.566ft (3.830m) of depth, where water depth was equaled to 1.283ft (391m). Then, two appraisal wells were drilled – 6507/3-3A, 6507/3-3B – to depths around 14.025ft (4,275m) to confirm presence of hydrocarbons.
Next, on 25.03.1999 the two appraisal wells were abandoned and classified as gas discovery.

2.1.4 Production

The beginning of production at the field is planned on 3rd quarter of current year (2011).
Oil production peak is estimated to reach 85.000 bopd.
The life expectancy of the reserves is assessed to 25 years.
Gas from the field is going to be transported via Åsgard pipeline to processing plant in Karstø. However, oil is going to be unloaded to tankers every week.

Main operating unit at the field will be Floating Production Storage Offloading – FPSO vessel with storage capacity of 875.000 barrels of oil.

Skarv/Idun field consists of 16 wells: 7 oil wells, 5 gas and condensate wells, 4 injection wells.
As an interesting fact, to prevent hydrates, experimental solution has been applied – electrically heated flow lines on the whole length.

2.2 Geological aspects

Lithology

Well 6507/5-3 was used as a reference for the various formations.

Depths are in m below MSL (Mean Sea Level).

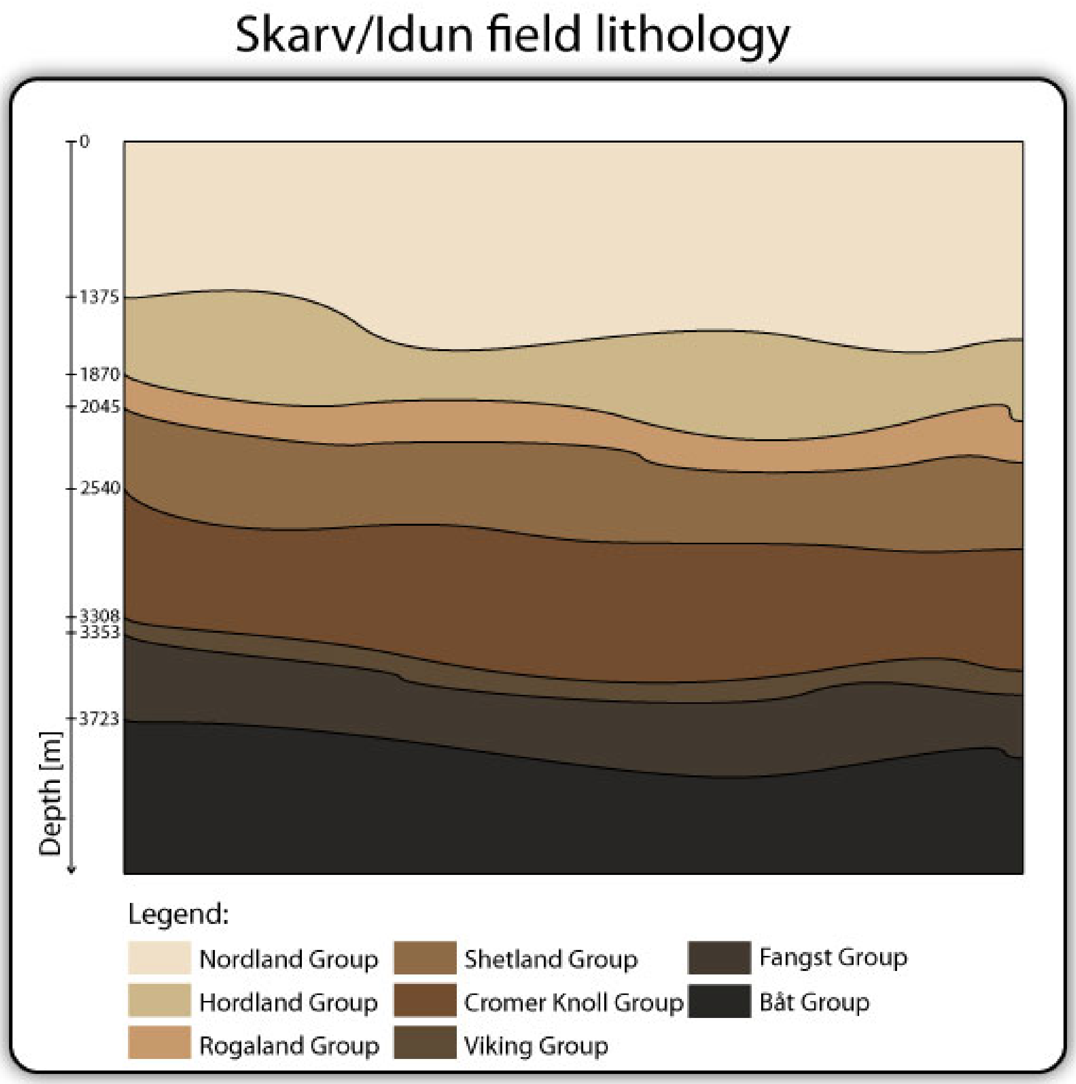


Fig. 4. Skarv/Idun field lithology

Following formation groups can be found at Skarv/Idun field:

<u>Nordland Group</u> (seabed – 1375m)

It consists of the Naust and Kai Fm that are upper glacial deposits. The formation mainly consists of silty to sandy clay and clay stones, with inter-bedded sands and some limestone stringers.

Hordaland Group (1375m – 1870m)

Brygge Fm, which is a marine deposit, is the main formation of the Hordaland Group. The group consists of silty to sandy clay stone with stringers of sandstone and limestone in the middle part of the formation.

Tuffaceous clay stone occurs in the lower and partly in the middle part. However, limestone can be observed in the upper part.

Rogaland Group (1870m – 2045m)

Tare and Tang Fm, which are marine deposits, make up main formations of the Rogaland Group. They consist of clay stone with stringers of limestone with some dolomite.

Shetland Group (2045m – 2540m)

The Shetland Group is made up by Nise and Kvitnos Fm.The first consists of mudstones with some dolomite stringers, while the second one consists of mudstone with limestone stringers.

Cromer Knoll Group (2540m – 3308m)

Lysning and Lange Fm are main formations that make up the Cromer Knoll Group. The Lysning consists of fine-grained, argillaceous sandstone. The Lange Fm consists of mudstone with fine-grained sands and limestone stringers.

It has to be emphasized that not all the exploration wells have encountered these formations on Skarv/Idun area.

Viking Group (3308m – 3353m)

The Viking Group is made up by two formations: Spekk and Melke Fm. The first consists of organic rich clay stone with some traces of limestone and dolomite. The second of them consists of mudstone with silty intervals and frequent stingers of dolomite.

Fangst Group (3353m – 3723m)

The Fangst Group is represented by three formations: Garn, Not and Ile Fm. The first one mainly consists of thick sandstone. The upper part of the second one – Not Fm – is made up

by sandstone, gradually fining downwards to siltstone. In the upper part of the last formation – Ile Fm – we can observe argillaceous sandstone with minor inter-bedded clay stone stringers.
Mentioned in the beginning, the Garn Fm, represents the main reservoir for the development.

<u>Båt Group</u> (3723m – TD)
The Båt Group consists of three formations: Ror, Tilje and Åre Fm. Top part of the Ror Fm is made up by sandstone and thin shale layers, however the lower one consists of siltstone, grading to sandstone and silty sandstone.
The Tilje Fm is represented by sandstone, with thin inter-bedded mudstone layers.
The last one – Åre Fm – consists of inter-bedded sandstone, clay stone, shale and dolomite rich limestone with some traces of coal.
The Tilje FM is going to be developed in the Skarv A segment as it contains hydrocarbons.

2.3. Wellbore conditions

2.3.1 Temperature

When we assume that seabed temperature is 5C, the temperature gradient is equaled to $3{,}9°C/100m$ with a range between $3{,}7°C/100m$ to $4{,}2°C/100m$.

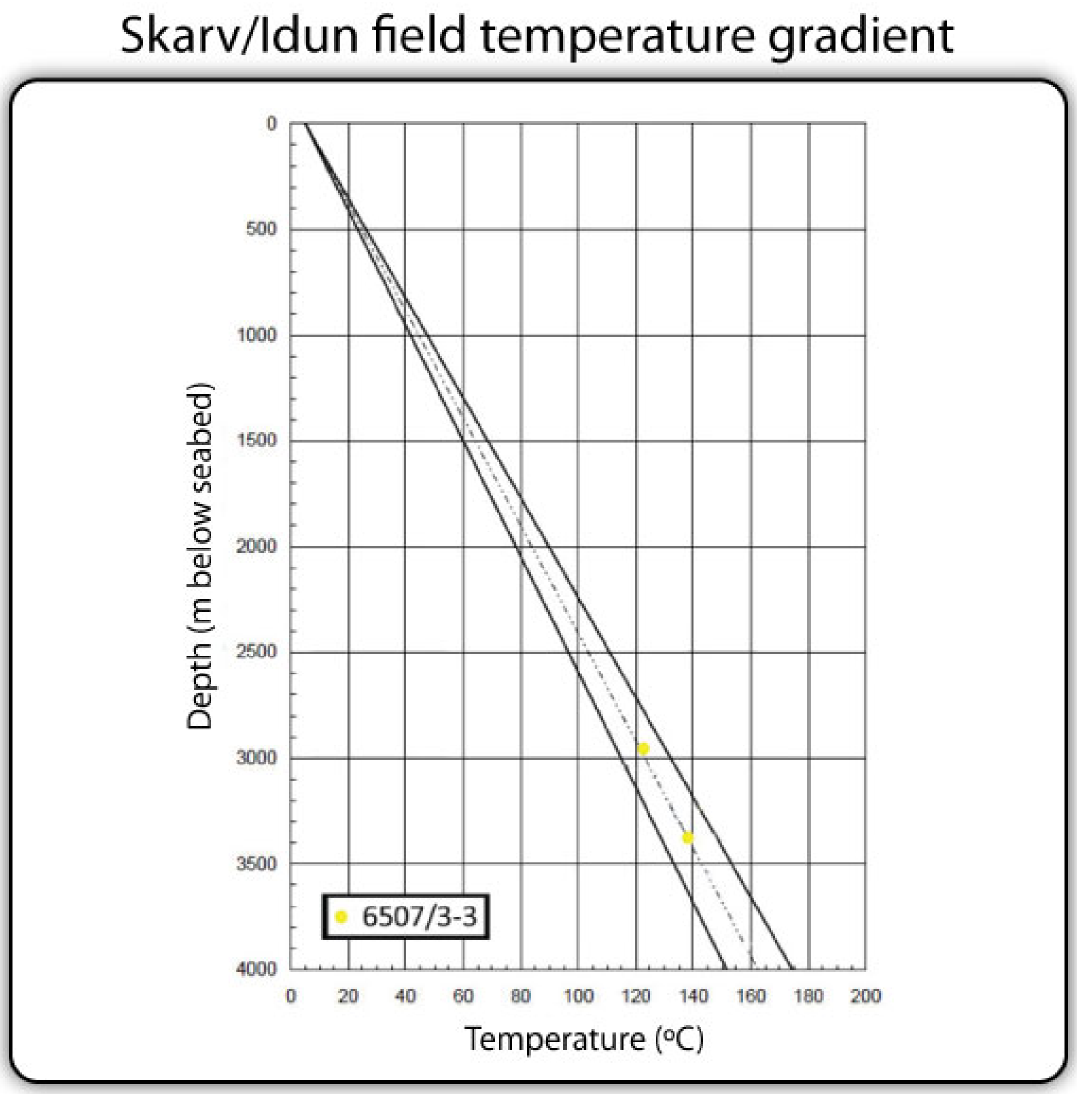


Fig. 5. Skarv/Idun field temperature gradient

2.3.2 Pore pressure

When describing pore pressure, just Idun 6507/5-3 well will be taken into consideration.

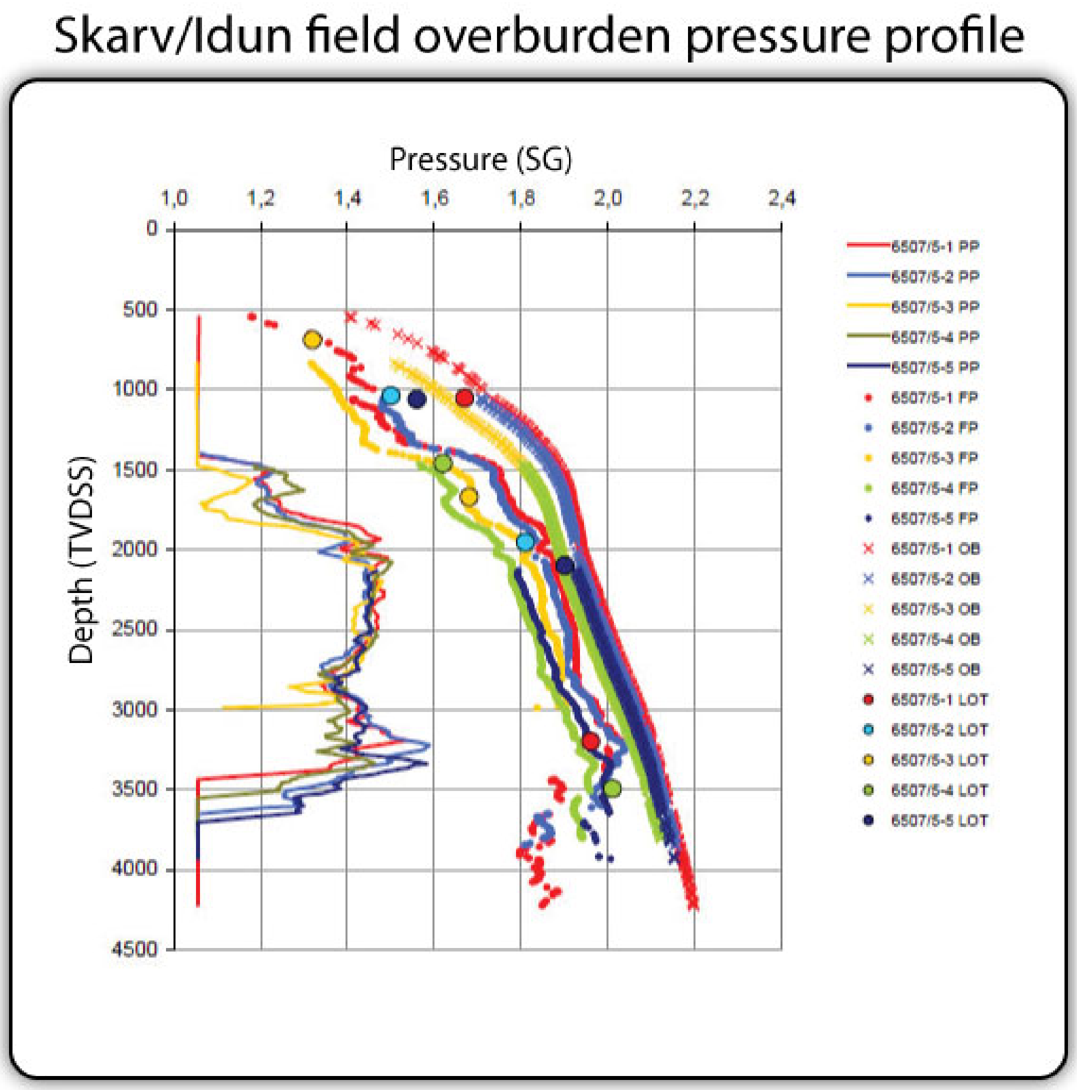


Fig. 6. Skarv/Idun field overburden pressure profile

At a distance from seabed to 1.695m MSL depth, a normal pore pressure gradient of 1,03 sge is estimated and then, it starts to increase. Then, at depth of 1975m MSL the pressure gradient reaches 1,42 sge.

At 3.175m MSL a pressure of 1,52 sge is estimated and moreover, it is maximum calculated pore pressure in the well. From this depth a decline takes place down Top Garn Fm where pressure of 1,12 sge was measured.

In the Fangst Group, to top Åre, a gas gradient of 0,2 sge is measured.

Between Åre and Tilje a pressure shift of 3 bar is estimated.

From gas/water contact observed at depth of 3.670m MSL a pressure gradient of 1,045 sge can be observed.

Pressure profiles were estimated using conic compression data in shale sections and formation pressure points from wire line tools in sandy sections.

2.3.3 Fracture gradients

When describing fracture gradients, just Idun 6507/3-3 well will be taken into consideration.

Skarv/Idun field fracture gradients

					20"-18 3/4" shoe				13 3/8" shoe			
Operator	Drilled	Well	RT-MSL m	Water Depth m MSL	Original Shoe Depth m TV RT	Original LOT EMW SG	Recalc. Shoe Depth m TV MSL	Recalc. LOT EMW SG	Original Shoe Depth m TV RT	Original LOT EMW SG	Recalc. Shoe Depth m TV MSL	Recalc. LOT EMW SG
Amoco	1998	6507/5-1	23	327	1053	1.664	1030	1.701				
Saga	1991	6507/6-2	18	315	1040	1.712	1022	1.742	2028	1.666	2010	1.681
Hydro	1992	6507/2-2	23	384	671	1.480	648	1.533	1399	1.720	1376	1.749
Hydro	1994	6507/2-3	22	355	1453	1.691	1431	1.717	2002	1.665	1980	1.684
Statoil	1999	6507/3-3	25	391	667	1.276	642	1.326	1752	1.650*	1727	1.674*
BP Amoco	1999	6507/5-2	18	347	1037	1.510	1019	1.537	1954	1.810	1936	1.827
BP Amoco	2000	6507/5-3	36	417	688	1.320	652	1.393	1670	1.680	1634	1.717
BP Amoco	2001	6507/5-4	25	421	1460	1.620	1435	1.648				
BP Amoco	2002	6507/5-5	18	375	1051	1.560	1033	1.587	2100	1.900	2082	1.916

					9 5/8" shoe				7" shoe			
Operator	Drilled	Well	RT-MSL m	Water Depth m	Original Shoe Depth m TV RT	Original LOT EMW SG	Recalc. Shoe Depth m TV MSL	Recalc. LOT EMW SG	Original Shoe Depth m TV RT	Original LOT EMW SG	Recalc. Shoe Depth m TV MSL	Recalc. LOT EMW SG
Amoco	1998	6507/5-1	23	327	3199	1.960	3176	1.974				
Saga	1991	6507/6-2	18	315	3303	1.992	3285	2.003				
Hydro	1992	6507/2-2	23	384	2761	2.020	2738	2.037	3322	2.000*	3299	2.014*
Hydro	1994	6507/2-3	22	355	3044	1.920	3022	1.934				
Statoil	1999	6507/3-3	25	391	3355	1.590*	3330	1.602*				
BP Amoco	1999	6507/5-2	18	347								
BP Amoco	2000	6507/5-3	36	417								
BP Amoco	2001	6507/5-4	25	421	3494	2.010*	3469	2.024*				
BP Amoco	2002	6507/5-5	18	375								

Fig. 7. Skarv/Idun field fracture gradients

Just one LOT (Leak Of Test) in the well – 6507/3-3 – was taken below 20” casing shoe at 642m MSL and showed a value of 1,32 sge. At 13 3/8” casing shoe, at depth of 1727m MSL FIT to 1,67 sge was taken. Another FIT to 1.60 sge was taken at the 9 5/8” casing shoe, at depth of 3.330m MSL.

2.3.4 Boulders

Skarv/Idun area is known for the presence of boulders in the top-hole section.

Boulders were encountered just at the interval between 421m MSL and 423m MSL.

No serious problems occurred with keeping minimal hole inclination while drilling.

3. Wellbore design qualification

3.1 Well design requirements

While designing a well to be drilled, there are some directives from above regarding wellbore requirements. They refer to design & drilling process, drill string design, geological data as well as other issues related to, for example, measurements.

We can divide well-preparation requirements to a few groups:

- trajectory design requirements
- geological requirements
- operational requirements

Main trajectory requirements regarding the well that is being designed are:

- torque & drag will be kept to minimum
- dogleg severity (DLS) of $1{,}5° - 2{,}0° / 30m$ at Kick Off Point (KOP)
- average dogleg severity (DLS) of $2{,}0° - 3{,}0° / 30m$ in 17 ½" and 12 ¼" sections
- maximal dogleg severity (DLS) of $4{,}75° / 30m$ for horizontal wells
- use of 3D Rotary Steerable System (RSS)

Main geological requirements are first and foremost:

- consideration (in the design of trajectories and selection of downhole targets) of stratigraphical features: presence of major faults, uncertainties, formation/marker tops.
- reservoir entry angle requirements
- formation drill-ability requirements (considered in relation to entry level and steerable equipment solutions)

Main operational requirements are:

- MWD system (in 26" section): Gyro or Gyro/MWD
- LWD system (with reservation that log quality will be as good as wireline logging)
- open hole wire-line and pipe conveyed logging: in vertical/near vertical hole sections
- hole cleaning: RPM should be kept above 125 (to ensure good hole cleaning) + standard

hole cleaning trend plots

- completion: wireline access to a production packer

3.2 Design & size

Conceptual well is named 'Snadd Beta'. It consists of five sections, as following:

Interval	Type	Section	Azimuth	Inclination	DLS
[-]	[-]	[-]	[°]	[°]	[°/100ft]
1	Straight	Absolutely vertical	-	-	0
2	Curved	Deviated (build-up)	287,63° (no change)	1,44° - 61,92° (constant change)	3
3	Straight	Tangent	287,63° (no change)	61,92° (no change)	0
4	Curved	Deviated (build-up)	286,16°-195,02°	61,88° - 87,59° (constant change)	3
5	Straight	Horizontal	195,02° (no change)	87,59° (no change)	0

Tab. 1. 'Snadd beta' well structure

The pattern of the well can be presented in 3-D simplified view as the one o next page:

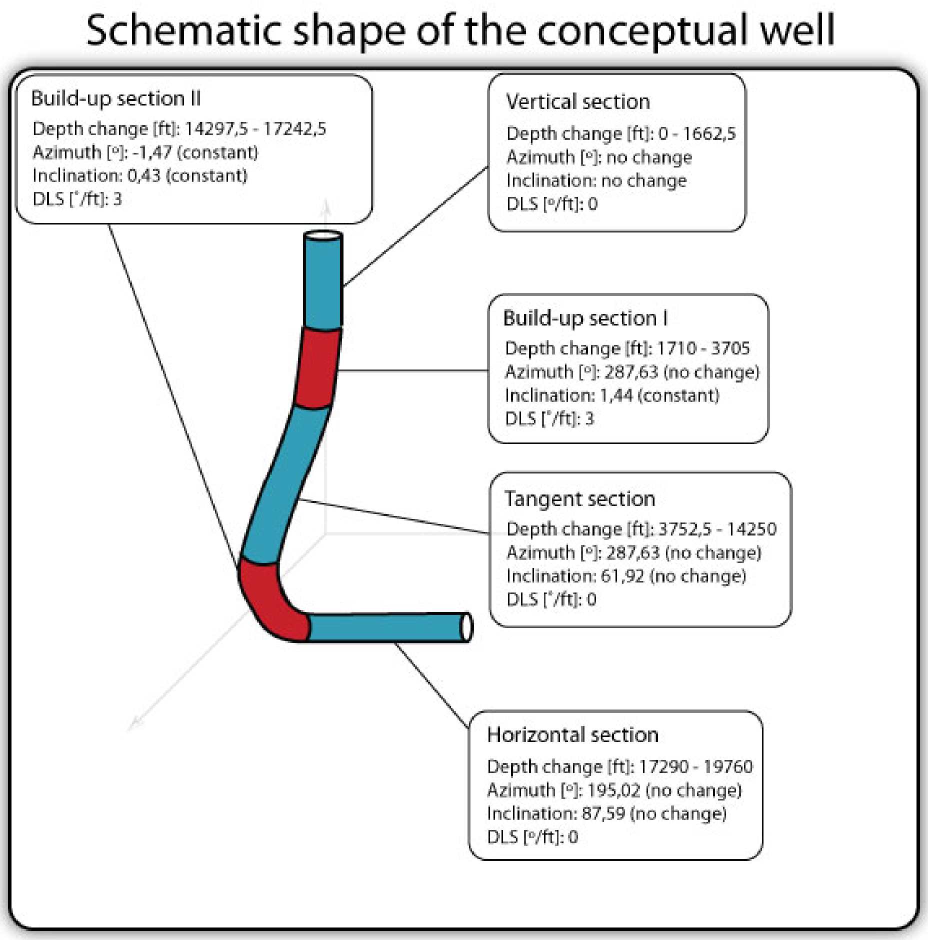


Fig. 8. Schematic shape of the conceptual well

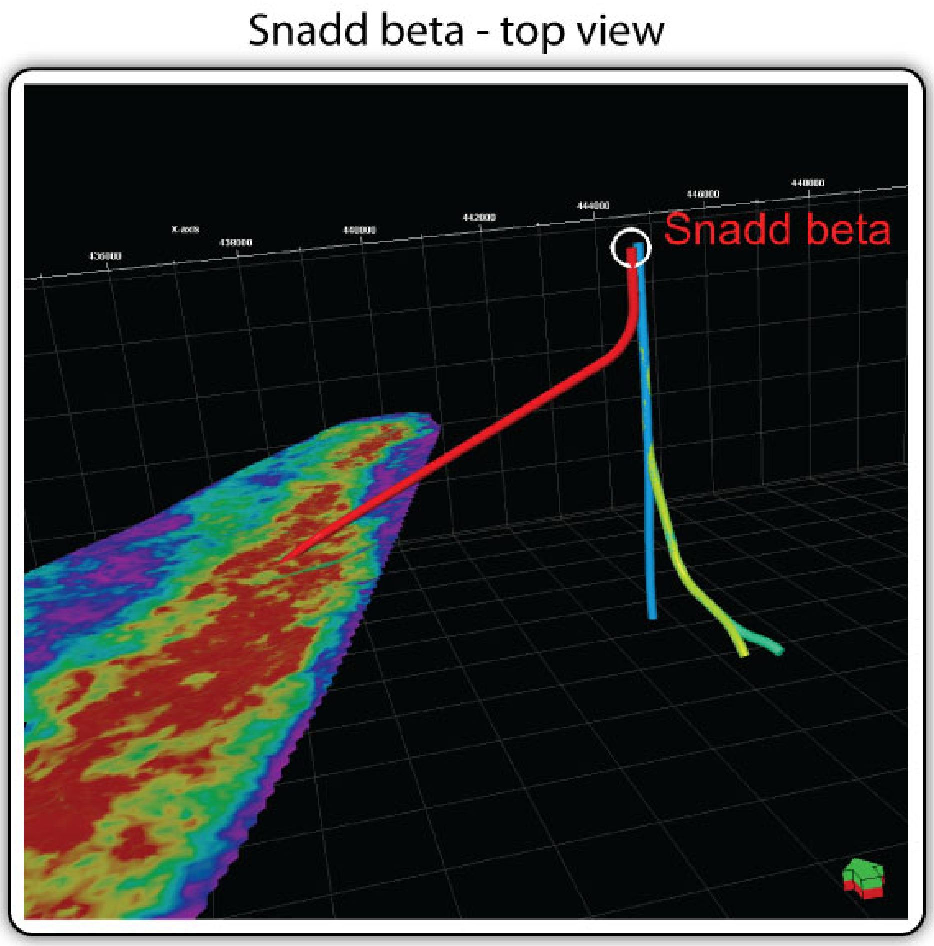


Fig. 9. 'Snadd beta' well - top view

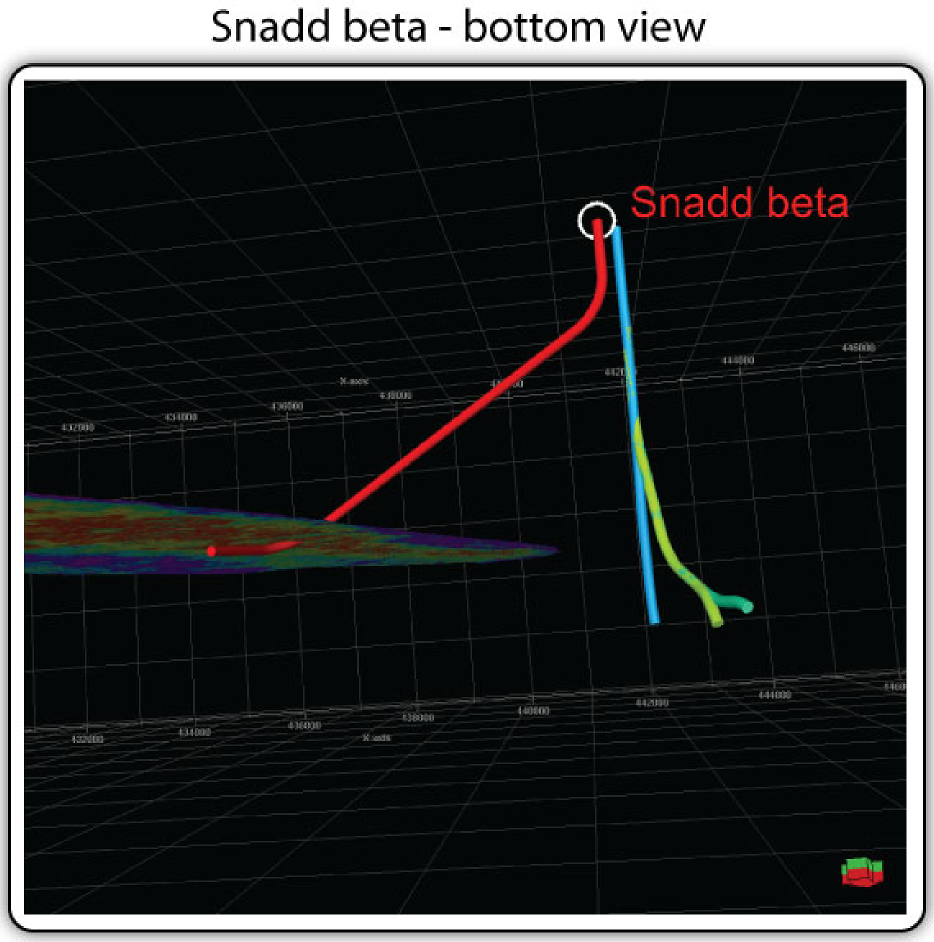


Fig. 10. 'Snadd beta' well - bottom view

First section of the well will be drilled with 36” drill bit, second one with 24” bit, third with 17 ½”, fourth one with 12 ¼” bit and finally the last section will be drilled with 8 ½” drill bit.

3.3 Depth

Overall Measured Depth of the well equals to 19.760,00 ft.

Step length between survey points was chosen to be 47,5 ft.

Moreover, as was said before, the well consists of 5 sections.

Depth and number of steps for each of the sections are presented below:

Interval	Section	Number of steps	Depth from	Depth to
[-]	[-]	[-]	[ft]	[ft]
1	Absolutely vertical	36	0	1.662,5

2	Deviated (build-up)	43	1.710	3.705
3	Tangent	222	3.752,5	14.250
4	Deviated (build-up)	63	14.297,5	17.242,5
5	Horizontal	53	17.290	19.760

Tab. 2. Sections depths of the conceptual well

'Step-length' of each section can be graphically presented as well, as follows:

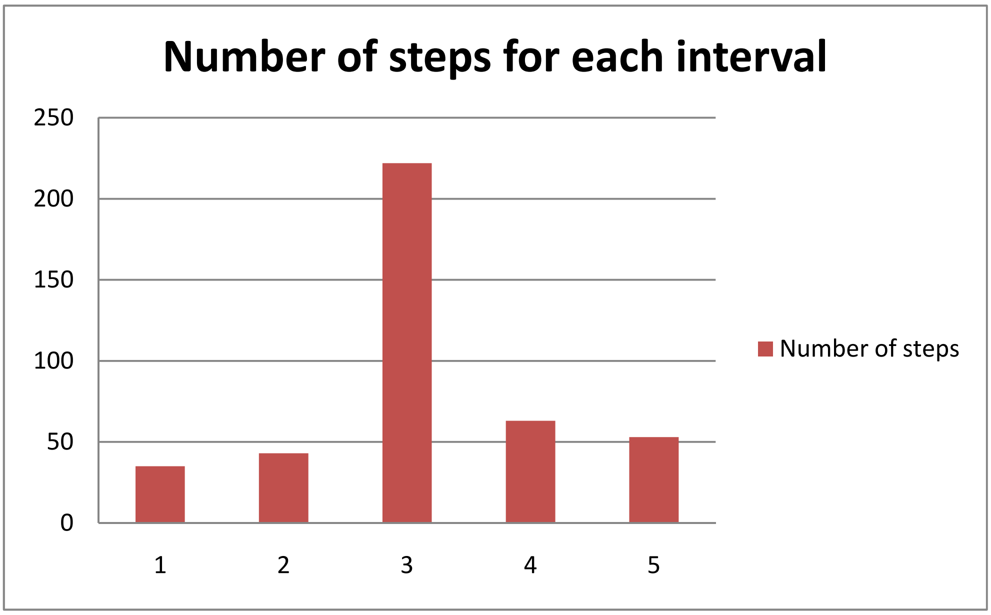


Fig. 11. Number of steps for each interval of the conceptual well

Also Measured Depth reached by each of the intervals is shown below:

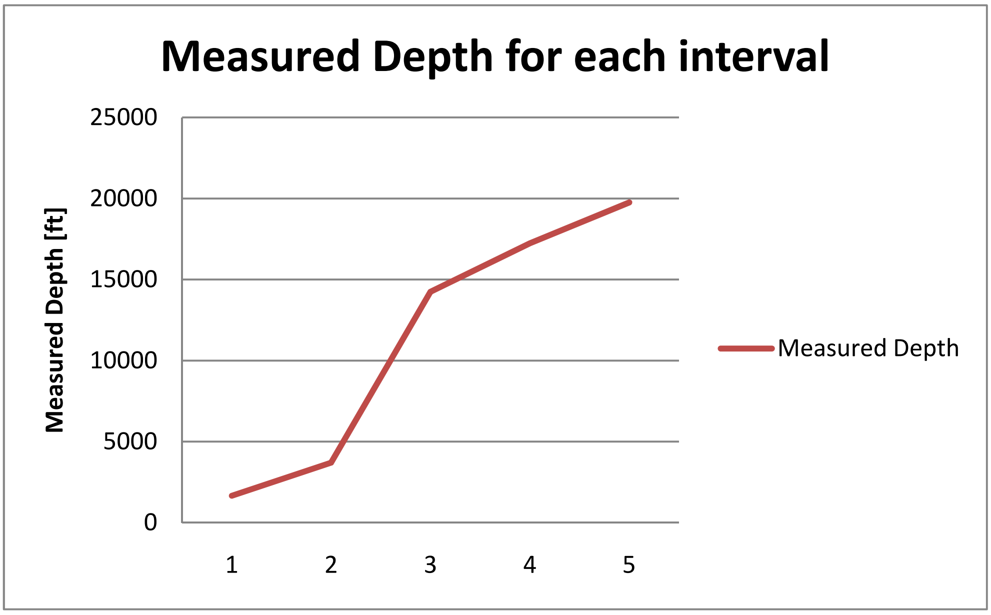


Fig. 12. Measured Depth for each interval of the conceptual well

3.4 Petrel software vs. Simplified Well Pattern comparison

To simplify the calculations regarding drag & torque modeling in the next chapters, some simplifications have been made to the well pattern, depth of each section as well as inclination and azimuth.

The most important changes made in the simplified model are shown below in the table. As the reference point values from Petrel model had been used.

Section	Factor	Petrel software	Simplified Well Pattern
[-]	[-]	[ft, °]	[ft, °]
Absolutely Vertical	Depth	1.640,50 ft	1.662,5 ft
Deviated (build-up)	Depth	3.691,88 ft	3.705 ft
	Inclination	1,45° (small deviation)	1,44° (constant change)
Tangent	Depth	14.247,25 ft	14.250 ft
	Inclination	62,52° (no change)	61,92° (no change)
Deviated (build-up)	Depth	17.226,53 ft	17.242,5 ft
	Inclination	0,41° (moderate deviation)	0,43° (constant change)
	Azimuth	1,46° (moderate deviation)	1,47° (constant change)
Horizontal	Depth	19.738,14 ft	19.760 ft

Tab. 3. 'Petrel' software and Simplified Well Pattern comparison

3.5 Simplified casing program

Casing program has been designed within the confines of casing requirements for wells on Skarv/Idun oil field.

Following columns of casing have been installed in the well:

Interval	Casing type	Hole size	Casing size	Depth from	Depth to
[-]	[-]	[inch]	[inch]	[ft]	[ft]
1	Conductor	36”	30”	0	1.662,50
2	Surface	24”	18 5/8”	1.662,50	5.741,75
3	Intermediate	17 ½”	13 5/8”	5.741,75	10.105,48
4	Production	12 ¼”	10 ¾” x 9 7/8”	10.105,48	17.225,25
5	Open hole	8 ½”	-	17.225,25	19.760

Tab. 4. Casing program for the conceptual well

3-D schematic view looks as following one:

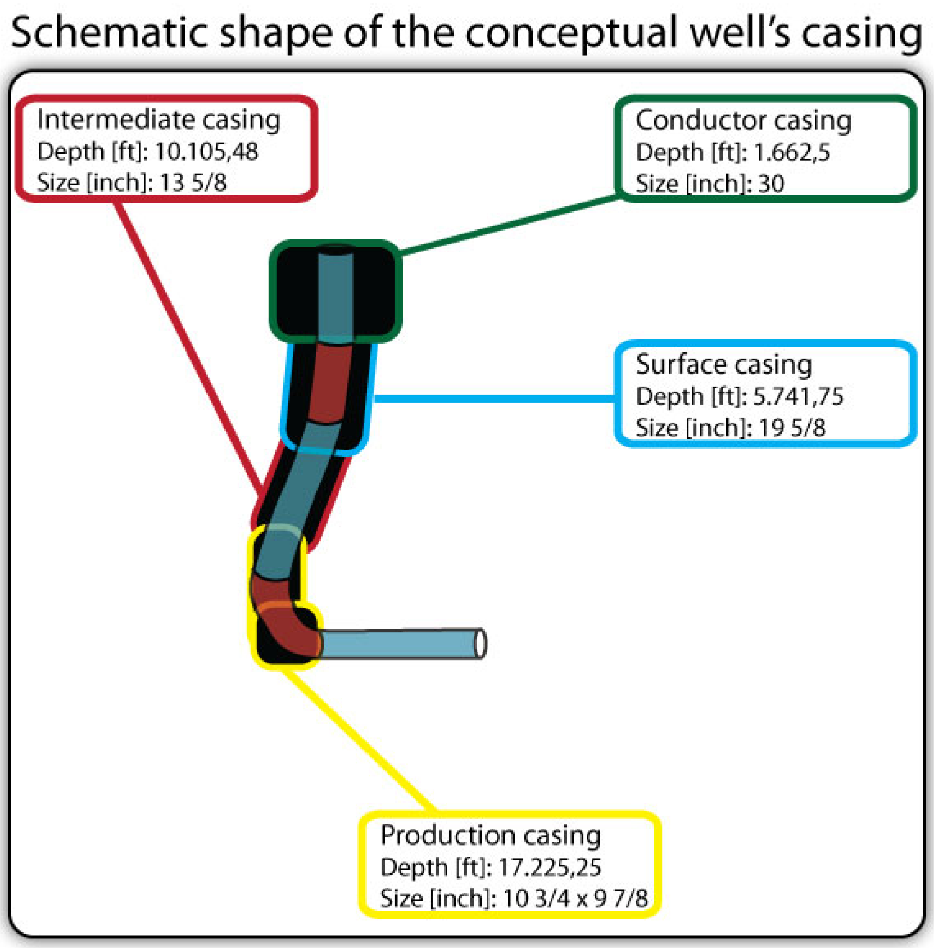


Fig. 13. Schematic shape of the conceptual well's casing

4. Available pipe options

4.1 Overview

Advances and continuous progress in wells complexity and drilling technology required to drill ultra-deep and Extended Reach Drilling wells. Nowadays, it is not just a problem of rig capabilities, it is more the problem of drill pipes performance factors, hole cleaning limitations and high-torque connections. Meeting the requirements of deepwater, harsh environments and extremely difficult well profiles is a challenge for every drill pipes manufacturer.

Deeper and deeper wells with complex patterns require drill strings with improved properties such as:

- increased tensile load capability
- greater torque capacity
- higher strength-to-weight ratio

All of the foregoing factors serve to overcome such problems as:

- frictional drag forces
- inefficient hydraulic performance
- poor rate of penetration
- control of well trajectory
- weak hole cleaning

With detailed selection of pipe material and size for given wellbore conditions, it is possible to improve drilling performance efficiency, facilitate utilization process and reduce costs. Examples of such selection are presented below.

4.2 Selection basics

In 'Detailed pipe selection' chapter three sizes and three materials of drill pipes have been chosen. The selection has been done based on the assumptions from 'Wellbore design qualification' chapter. It is worth mentioning that hydraulic issues affecting drill string design have not been considered due to increased complexity of the thesis.

Three materials that have been chosen are:

- Steel S-135
- Aluminum 2014-T6
- Composite (e-glass/graphite/epoxy)

Four sizes that have been chosen are:

- 3 3/8" drill pipe
- 4 ½" drill pipes
- 5" drill pipes
- 5 ½" drill pipes

Description and specification for each of mentioned-above drill pipes are available below.

Properties that have been included are:

Materials	Pipes
- Young's modulus [kN/mm^2] - material density [g/cm^3]	- outside Diameter [in] - outside Diameter [mm] - nominal weight [lb/ft] - wall thickness of the pipe [mm] - inside Diameter [in] - inside Diameter [mm] - cross section [mm^2] - polar moment of inertia [mm^4] - polar modulus [mm^3] - type of tool joint - tool joint Outside Diameter [mm] - tool joint Inside Diameter [mm] - approximate weight including tool joint [lb/ft]

Tab. 5. Properties included in pipe description

4.3 Steel pipes

4.3.1 Overview

S-135 drill pipes are commonly used in the petroleum industry. They offer satisfactory properties, thereby keep a reasonable price. They are also often used as a reference point to show characteristics of pipes made of other materials such as aluminum, composite or titanium, which are presented in further part of the chapter.

4.3.2 Manufacturing

Steel pipes are produced with two distinct methods that result in seamless or welded pipe. The general overview of manufacturing process looks like that. First, a raw steel cast to a more workable starting form. Then, the pipe is formed on a continuous or semi-continuous production line. Finally, the pipe is cut and specially modified to meet the customer's needs.

4.3.3 Advantages vs. drawbacks

Advantages	Drawbacks
- good durability	- huge weight
- satisfactory mechanical properties	- poor flexibility
- relatively low production cost	- bad electric/magnetic properties
- wide range of sizes	- average wear resistance
- easily available	

Tab. 6. Advantages and drawbacks comparison for steel pipes

4.3.4 Possible ways of improvement

Possible way of improvements of steel drill pipes include:

- use of ultra-high strength steels (for Extended Reach Drilling and Ultra Deepwater Drilling)
- increase of strength-to-weight ratio
- application of ultra-high torque rotary shoulder connection
- limit of wear phenomenon & temperature resistance increase through better selection of used alloys
- cost cut down

4.3.5 Conclusion

S-135 drill pipes that are available on the market are commercially used for majority of field works, where for the sake of drilling conditions, pipes with increased resistance are required. They are characterized mainly by increased fatigue resistance. Good durability and mechanical properties are main advantages. Huge weight and poor flexibility prevent the pipes to be used in extreme conditions such as Extended Reach Wells with long horizontal sections or short-radius bents.

However, taking into consideration strength-to-weight ratio and production cost, they can be utilized in majority of oil fields, where harsh environment doesn't occur.

4.3.6 Specification

Material mechanical properties and detailed pipe specification are available in the end of the chapter.

4.4 Aluminum pipes

4.4.1 Overview

Drill pipes made of aluminum have been used in the petroleum industry for dozens of years. Most of experience with the pipes comes from Russia, where they are used pretty extensively. Based on facts from the history, use of aluminum pipes is reliable and proven technology. Moreover, Aluminum Drill Pipes were used in North and South America, but on a limited basis. Main reasons of such an operation were to extend the depth reach of existing rigs, as well as to facilitate transportation of Heli-transported rigs.
Sometimes Aluminum Drill Pipes are called as the 'poor man's' of Titanium Drill Pipes, because of the fact that they share some of advantages, thereby keeping lower costs.

4.4.2 Manufacturing

The pipes are made from forged aluminum tubes that have upset ends. Tool joints (threaded steel) are bucked on to the tubes with either a shrink-fit connection of with some type of adhesive in the threaded region to secure the two members.

4.4.3 Advantages vs. drawbacks

Advantages	Drawbacks
- lower weight - good corrosion resistance - enhanced fatigue resistance - non-magnetic - superior horizontal drilling characteristics	- cost (about twice that of conventional steel drill pipe) - relatively low yield strength (especially over $250°F$) - lower strength-to-weight ratio (in compare to Ultra-Height-Strength steel drill pipe) - decreased hydraulic performance (greater wall thickness)

Tab. 7. Advantages and drawbacks comparison for aluminum pipes

4.4.4 Possible ways of improvement

- application of steel tool joints in aluminum drill pipes (increased resistance to torsional loads)
- application of ultra-high torque rotary shoulder connection
- fatigue performance increase
- high temperature resistance

4.4.5 Conclusion

Aluminum Drill Pipes can be utilized in Extended Reach Drilling or Horizontal Drilling, however they have many disadvantages as well, especially when relates to Ultra Deep Water drilling. First and foremost, low yield strength can be a significant problem.
Moreover, increased wall thickness that compensates durability limit influences hydraulic performance in undesirable manner. Finally, low temperature resistance affects fatigue resistance.
All in all, considering all pros and cons, Aluminum Drill Pipes can be an interesting alternative to Steel Drill Pipes, with the exception of harsh environment conditions.

4.4.6 Specification

Material mechanical properties and detailed pipe specification are available in the end of the chapter.

4.5 Composite pipes

4.5.1 Overview

Industry has been moving into direction of Extended Reach Drilling and Ultra Deepwater Drilling. Thus, participation of non-steel materials, such as carbon fiber composites, titanium, aluminum, has increased significantly.

First of above-mentioned materials is used rarely, but successfully, especially in short-radius and ultra-short radius drilling. Also in less complex conditions, the pipes will be examined.

4.5.2 Manufacturing

Composite Drill Pipes are manufactured by winding carbon fibers over a mandrel, while applying an epoxy matrix that encases the fibers and seals the assembly. The pipes have incorporated, as in steel drill pipe connections, steel pin and box tool joints. The steel tool joints are attached to the composite tube during the winding process where the carbon fibers are placed over specially designed tool joint ends to bond with the composite tube and resist fatigue damage in service.

4.5.3 Advantages vs. drawbacks

Advantages	Drawbacks
- lower weight - higher strength-to-weight ratio - superior corrosion resistance - enhanced fatigue resistance - non-magnetic - huge flexibility - very good fatigue resistance	- decreased hydraulic performance and efficiency - cost (three times the cost of conventional steel drill pipe)

Tab. 8. Advantages and drawbacks comparison for composite pipes

4.5.4 Possible way of improvement

- wall thickness decrease
- increase in OD (already utilized 5 $^{7/8}$" drill pipe with improved hydraulics)
- production cost decrease

4.5.5 Conclusion

Non-steel drill strings are primarily used to decrease values of torque and drag while drilling directionally. Composite Drill Pipes are one of the most significant factors that contribute to decrease resisting forces in a well. However, they cannot be used everywhere. The most limiting factor to use them commercially is production cost.

Moreover, increased wall thickness, thereby decreased ID, do not let the pipe to be used in complex well patterns, because of upset hydraulics.

4.5.6 Specification

Material mechanical properties and detailed pipe specification are available in the end of the chapter.

Material	OD		Nominal weight	Wall thickness of pipe body	ID		Cross section	Polar moment of inertia	Polar modulus	Type of tool joint	Tool joint OD	Tool joint ID	Approximate weight including tool joint
	[in]	[mm]	[lb/ft]	[mm]	[in]	[mm]	[mm^2]	[mm^4]	[mm^3]		[mm]	[mm]	[lb/ft]
S-135	4 ½	114,30	20,00	10,92	3,64	92,46	3.547	9.581.665	167.658	NC50 (IF)	168,30	76,20	23,06
S-135	5	127,00	25,60	12,70	4,00	101,60	4.560	15.078.604	237.458	NC50 (XH)	168,30	69,90	28,28
S-135	5 ½	139,70	24,70	10,54	4,67	118,62	4.277	17.955.483	257.058	FH	190,50	76,20	28,85
2014-T6	4 ½ (4,60)	116,84	8,40	12,70	3,60	91,44	4.155	11.432.932	195.694	NC50 (IF)	155,58	N/A	11,30
2014-T6	5 (5,15)	130,81	10,20	13,34	4,10	104,14	4,921	17.198.063	262.947	FH	177,80	N/A	13,70
2014-T6	5 ½ (5,68)	144,27	10,70	12,70	4,68	118,87	5,249	22.929.362	317.876	IF	187,33	N/A	14,60
Composite	3 3/8 (2,50)	63,50	N/A	11,11	1,625	41,28	1.829	1.311.153	N/A	NC26	85,73	41,28	3,067
Composite	5 ½ (6,00)	152,40	N/A	12,70	5,00	127,00	5.574	27.419.358	N/A	NC56	177,80	127,00	12,50

Tab. 9. Pipes' specification

5. Theoretical models

5.1 Fatigue resistance

5.1.1 Definition

Fatigue (in material science) is a progressive and localized structural damage that comes into being, when a material is exposed to recurrent loadings.
The strength of the material (especially metal, because we're interested in pipes' material) usually relates to static conditions – tension or compression.
The nominal stress values are smaller than the ultimate tensile stress limit, and usually are below the yield stress limit of the given material.

5.1.2 Way of a measurement

Let assume that there is a given specimen, which is exposed to dynamic conditions, it is obvious that after some time of working of external forces, the specimen may fail.
Then, it is said that the failure has been caused due to fatigue. To be able to predict time of the failure, suitable model has been developed, using fatigue machine.

The fatigue machine is quite simple rotating solution. A rod of the testing material is placed inside. At one end of the rod, force is applied to provide a bending stress. Then, the machine is rotated. Inside the rod a cyclic bending stress can be seen. To check fatigue resistance of the specimen, applied force has to be increased, until failure. More than a few samples have to be used to a strength curve for the material.
Finally, after gathering appropriate data, results can be plotted in a diagram, similarly to the one shown below.

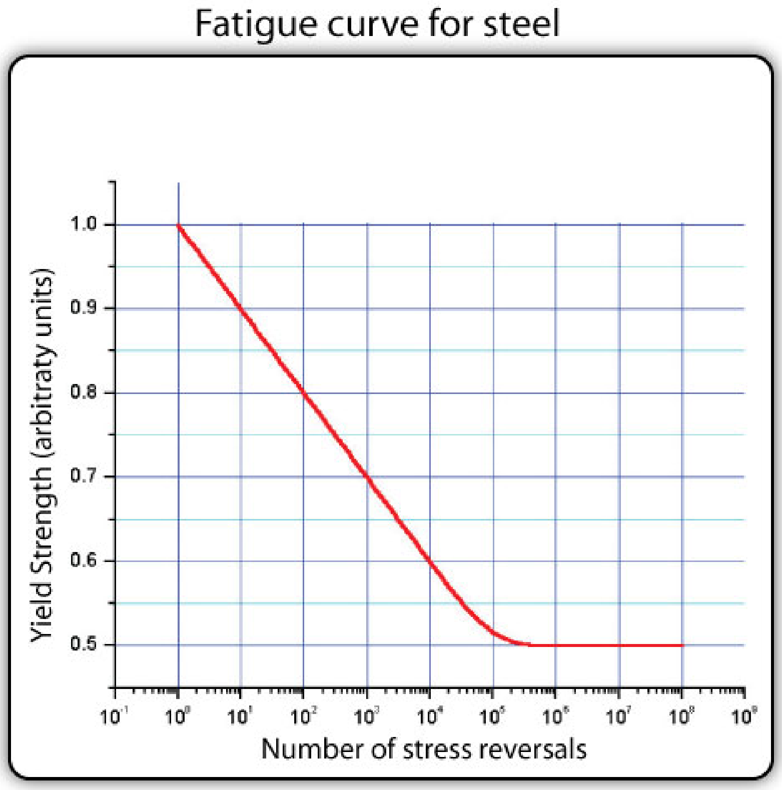


Fig. 14. Fatigue curve for steel

The diagram depicts fatigue resistance of steel while drilling throw hard formation.
When the load was 45 kpsi, the test rod took around 15.000 cycles to failure. When the load was decreased to 39 kpsi, around 41.000 cycles could be applied before driving to failure.
Going further, decreasing the load to 31 kpsi, effected to 400.000 cycles before failure.
The most important value in the graph is 27 kpsi, because at the point the metal will not fail for any number of cycles. It is called endurance point and concerns 40% - 60% of the static strength for most steels.
Most of other metals, that will be shown later in the thesis, do not experience the property, having continuously decreasing S-N curve.

5.1.3 Factors affecting fatigue resistance

One of the most important factors affecting fatigue resistance, especially in dynamic conditions, is the surface finish.

Following factors have huge influence on resistance of a given sample:

- material type (composites and polymers differ from metals)
- residual stresses (welding, cutting can produce tensile residual stress)
- small cracks (act as fracture initiation point)
- non-polished critical points (significantly decrease tensile strength)

- forged parts (offer weaker resistance)

- inappropriate geometry (cause stress concentration effect* that leads to failure)

- size and distribution of internal effects (casting defects and shrinkage voids can significantly reduce fatigue strength)

- environment (erosion, corrosion, hash environments can reduce fatigue meaningfully)

- temperature (extreme high or low temperatures weakens fatigue resistance throw external effect)

*Stress concentration effect relates especially to strength of a pipe. The problem is shown on the example of a drill collar connection. It has conical threads and lands on a flange. During connection makeup, pre-stress on the flange appears, because of the moment that is applied. Due to pre-stress and a complex geometry, internal stresses are created, reducing the externally applied load to failure.

All in all, the geometry is a main factor that cause stress concentrations, as shown below.

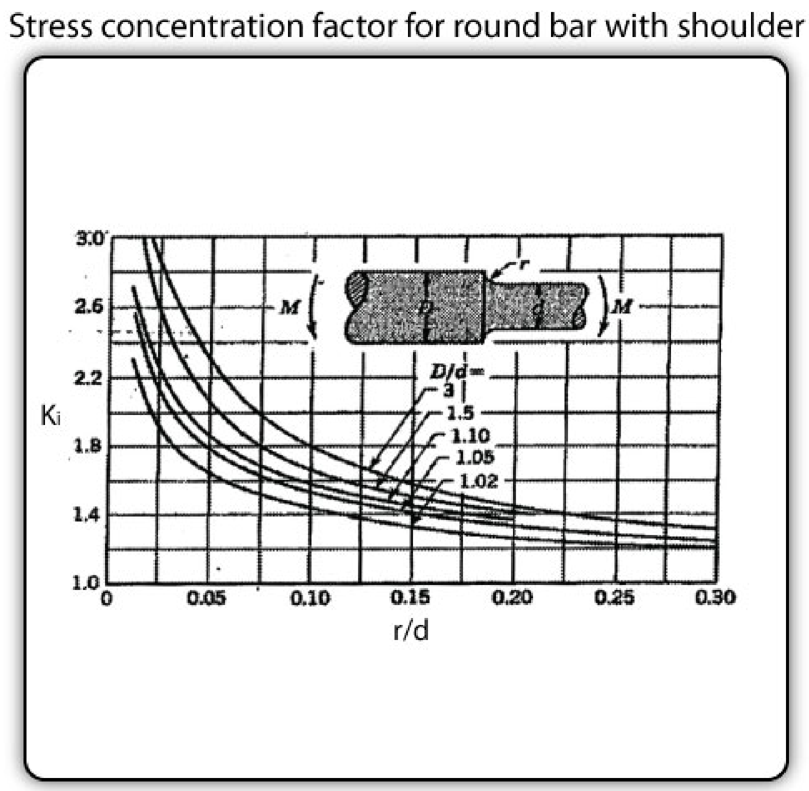


Fig. 15. Stress concentration factor for round bar with shoulder

Moreover, negative influence of geometry changes is visible as well. Thus, it should be kept to minimum.

Influence of surface finish on fatigue resistance of a given sample is shown below.

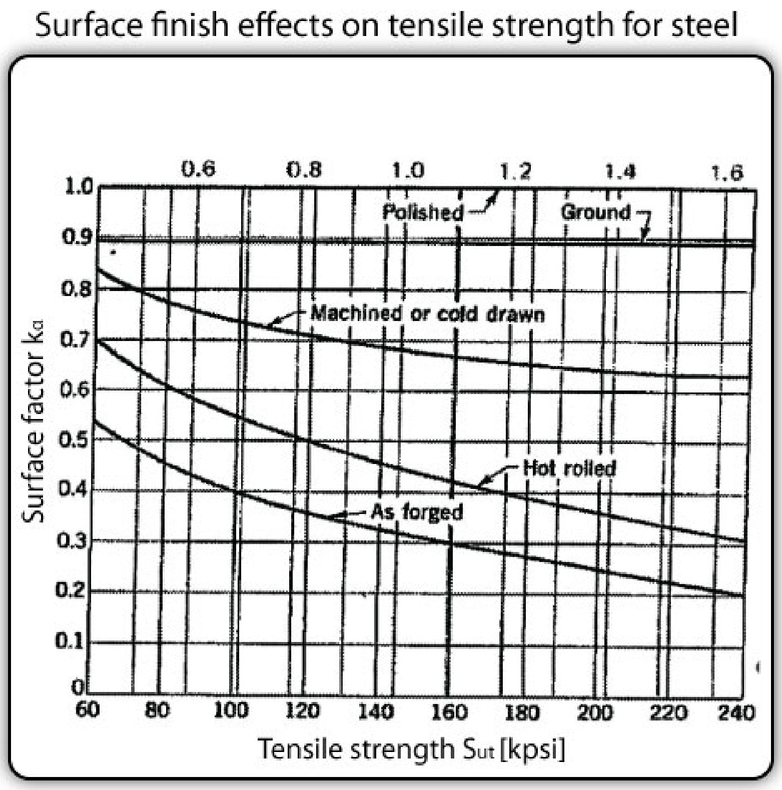


Fig. 16. Surface finish effects on tensile strength of steel

5.1.4 Fatigue-failure prevention

It is known that failures usually arise in stress conditions – tension or compression. Most of them occur in the Bottom-Hole-Assembly which appears mostly in the second of them. However, there are other places subjected to extreme loadings.

Since the time that drill collars are much stiffer than the drill pipes, transversal vibrations and bending stresses can lead to enormous strains at the connections.

And it is believed that these two factors (transversal vibrations and bending stresses) are the main cause of connection failure.

So a question comes to mind - what to do to prevent fatigue problems in the connections ? The answer is quite simple. Understanding the effect of stress concentration, it is highly important to decrease tension, while making a connection, between the pin and the box end of the given connection. Therefore, mentioned elements should be precisely polished to prevent inaccuracy of workmanship, thus preventing future fatigue problems.

5.2 Simplified torque & drag model

5.2.1 Endorsement

There are two types of drag & torque models commonly used in drilling engineering nowadays:

- simple 2-D model (just inclination is taken into consideration)
- simplified 3-D model (takes into consideration inclination and Azimuth as well)

Because of the fact that the 3-D model is a development of 2-D one, the study shown below is based especially on the 2-D model. Moreover, the profile of the thesis was changed while doing calculations, which means in practice that 3-D model had replaced 2-D one.

In the beginning, all of the calculations, assumptions, expressions are related to the 2-D one. However, in the end of the sub-chapter, calculations that are applicable in 3-D model were presented.

Summarizing up, the 3-D model had been applied in the thesis, so all of the 3-D calculations are used.

5.2.2 2-D torque & drag model

5.2.2.1 Overview

One of the most significant problems, if not the most significant, related to horizontal and extended reach drilling are torque and drag, which are caused by friction forces that affect a drill string and a wall of a hole.

The importance of drag and torque problem is determined by intensity of contact and interaction between the pipe and the hole, as well as by the friction coefficient that always occurs between them.

Forces related to an object, which is an example, on an incline are shown below.

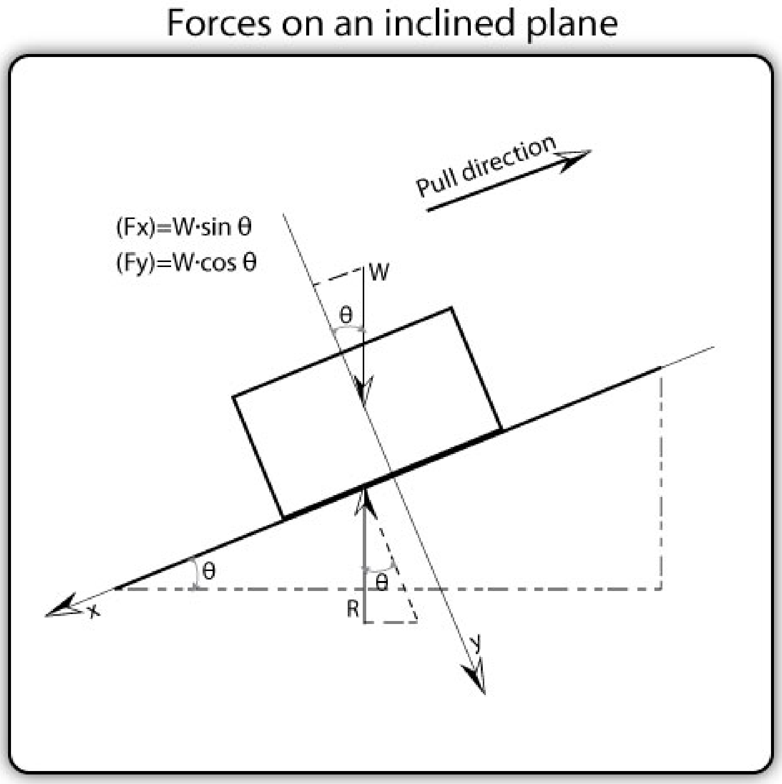


Fig. 17. Forces on an inclined plane

As we can see from the illustration that force required to move the object on frictionless basis (Fx) is equal to $W \cdot \sin\theta$

Friction is always present in interactions between things. It is always associated with an object, which has to be moved. The friction force equals to the normal force (used to move the object in frictionless environment) times friction factor.
Therefore, the force required to pull the block up the incline is expressed with:

$$T = -W \sin\vartheta + \mu W \cos\theta$$

Similarly, the force required to push the block down the incline is:

$$T = -W \sin\vartheta - \mu W \cos\theta$$

Where:

T - axial tension

W – buoyed weight of pipe

μ - friction coefficient

ϑ - angle of incline

Furthermore, for a plane, if $\mu W \cos\vartheta$ is greater than $W \sin\theta$, it is obvious that the object will have to be pushed down to set in motion. It works almost the same for the pipe in the well, however it is necessary to emphasize one thing - the incline of the plane is measured from horizontal, but the incline of the well is measured from the vertical. Thus, the pipe will have to be pushed down only when the inclination is equal to 90 less the angle of the incline.

It should be mentioned as well that tension required to move the block is completely independent on surface area. For drill pipes, it doesn't matter if the whole pipe touches the wall or just tool joints (which would be more natural occurrence). The drag values are the same in both cases.

It should also be written that friction is comprehended as contact between two solids. So, taking into consideration our case, when the pipe digs into the wall of the hole or when the hole is dirty, it is no longer just friction, but some external forces react as well, upsetting our simplified model. Therefore, drag and torque values will be higher than the one predicted. It is also worthy of recalling that drag and torque issues can occur in vertical well, especially when it is dirty or when we deal with wellbore stability problems.

5.2.2.2 Drag concept

As it has already been established, friction coefficient is one of the most important values affecting torque & drag. It depends mainly on two factors:

- drilling fluid in the wellbore
- roughness & unevenness of the wellbore walls

Usually, cased hole sections have lower friction coefficient than open hole sections.

When it refers to muds, water based have higher friction coefficient than oil based (0,25 to

0,40 for the first and 0,15 to 0,25 for the second). Furthermore, clear brines have even higher friction coefficient which is equal 0,30 to 0,40. However, the highest one belongs to air (while drilling) and equals to around 0,40 to 0,50.

In wells with lower inclination, drag is considerably low, however when it refers to high inclination, as well as extended reach horizontal wells, it can be very significant factor.

That is how it works. When we deal with a well with a hole curvature, to the normal force we have to add additional one that comes from pipes weight and the summed force poses majority of drag problems in deviated wells.

In the draft below, acting forces on the chosen pipe are shown.
The resultant normal force is the sum of two other forces:
- normal force due to tension
- normal force due to pipe weight

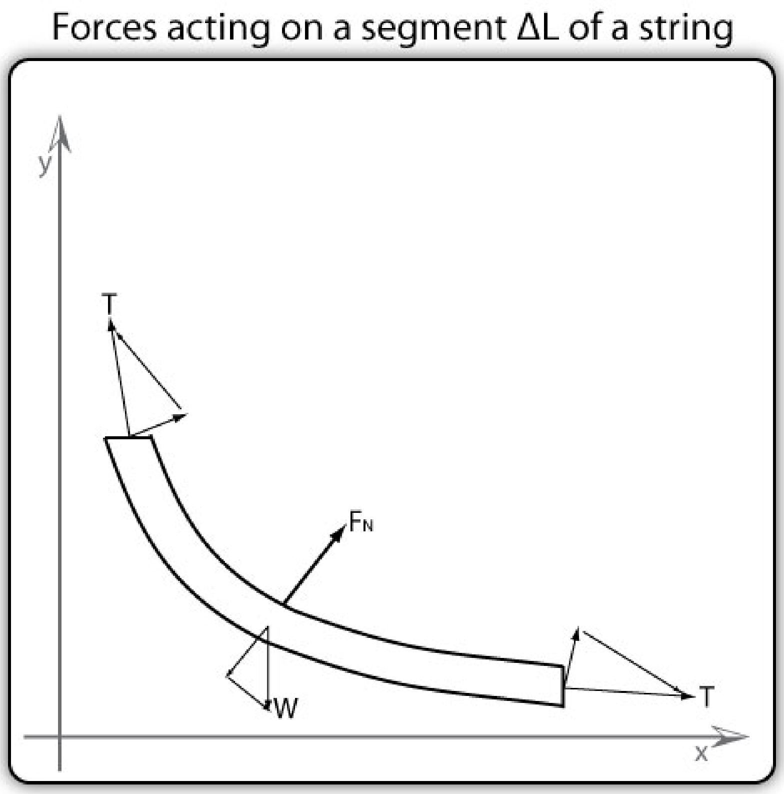


Fig. 18. Forces acting on a segment L of a string

Let’s assume that vertical plane is on the x-axis and similarly horizontal plane on the y-axis, then summing the forces in the x and y directions will obtain the normal forces:

Along x-axis:

(1) $F_x = 2T\sin\left(\frac{\Delta I}{2}\right) + W\sin I_{(avg)}$

Along y-axis:

(2) $F_y = 2T\sin\left(\frac{\Delta A}{2}\right)\sin I_{(avg)}$

Thus, vectorial sum of the foregoing forces is the resultant normal force due to tension and it looks like:

(3) $F_N = \sqrt{\left\{2T\sin\left(\frac{\Delta I}{2}\right) + W\sin I_{(avg)}\right\}^2 + \left\{2T\sin\left(\frac{\Delta A}{2}\right)\sin I_{(avg)}\right\}^2}$

Where:

F_N - resultant normal force

T - tension or tension in a drill string

ΔI - change in inclination over ΔL

ΔA - change in azimuth over ΔL

W - buoyant weight of segment ΔL

$I_{(avg)}$ - average inclination over ΔL

There are of course some limitations according to our calculations. First and foremost, the length of ΔL should not exceed 100 feet, to assure more accurate calculations. Then, the tension of the drill string has to be calculated before carrying out the drag & torque calculations.

It is worthy of remembering that drag forces work always in opposite direction than the string moves. So, while tripping out, the tension will reach higher values. And similarly, while tripping in, the tension will be decreased.

Forces acting while (3) tripping out and (4) tripping in can be calculated from following equations:

(4) $T_2 = T_1 - W \cos I_{(avg)} + \mu F_N$

(5) $T_2 = T_1 - W \cos I_{(avg)} - \mu F_N$

5.2.2.3 Buckling tendencies

Buckling causes additional resistance while tripping. Dawson and Paslay worked out an equation for sinusoidal buckling in inclined hole. Helical buckling will be omitted for the sake of its complexity in calculations, which would not be desirable in the simplified model. However, it is worth saying that helical buckling normally occurs after sinusoidal one.

Because of the fact, that buckling tendencies will be widely presented in other chapter, just Dawson and Paslay equation will be presented below, to simply visualize the problem.

(6) $F_{crit} = 2\sqrt{\frac{EI\rho Ag \sin I}{r}}$

Where:

E - Young's modulus

I - moment of inertia

ρ - pipe weight per cubic foot

A - cross sectional area of pipe

g - acceleration due to gravity

r - radial clearance between the outside diameter of a pipe and the hole wall

5.2.2.4 Torque concept

The torque phenomenon, in deviated wells, can be calculated from the same equations as the normal force, mentioned earlier in the chapter. However, there are dependences to be considered first:

- if pipe rotation nullifies drag forces, then hole drag is not considered
- if pipe rotation & movement are fast, then drag forces are not nullified (some drag will be still present while rotating the pipe)

While rotating, the tension at any point in the well will be calculated using the equation below:

(7) $T_2 = T_1 - W \cos I_{(avg)}$

Where:

T_2 - tension at the top of segment ΔL

T_1 - tension at the bottom of segment ΔL

W- buoyant weight of segment ΔL

The rotating weight will be the value T_2 at the surface.

The torque phenomenon, in our case, is dependent on the normal force. So when normal force is multiplied by friction coefficient, then the force resisting rotation of the drill string will be received.

So, to conclude the whole argument, the final equation to calculate desirable torque is given, as:

(8) $M_2 = M_1 + \mu F_N R$

Where:

M_2 - torque at the top of segment ΔL [ft-lbs]

M_1 - torque at the bottom of segment ΔL [ft-lbs]

μ - friction coefficient [-]

R - outside radius of pipe

It is worth emphasizing that, usually, that is the tool joint that touches the hole wall, so in place of 'R', radius of the given tool joint should be used.

All in all, it has to be said that there are two major factors affecting torque and drag values. First of them is tension and the second one is dogleg severity (DLS).
If even one of them increases, also drag and torque values will increase, which proves a thesis.

5.2.2.5 Critical inclination

To complete the chapter of drag and torque, calculation of critical inclination should be mentioned as well.
The critical inclination is a point from where a pipe has to be pushed further down to the hole, instead of moving without help of external forces. It entirely depends on friction coefficient.

The critical inclination can be obtained from the equation:

(9) $$I_c = \tan^{-1}\left(\frac{1}{\mu}\right)$$

Where:

I_c - critical inclination $[°]$

For example, for a friction coefficient of 0,4, the critical inclination is $68°$, whereas for a friction coefficient of 0,2 equals $79°$.

5.2.3 3-D torque & drag model

5.2.3.1 Overview

The basic 3-D model use the equations derived by Aadnoy (2009). A string in the model is treated as a heavy cable and it ignores tubular stiffness effects.

The equations define following values:

- hook loads (while pulling out and tripping in)
- drag forces (while pulling out and tripping in)
- torque (while pulling out and tripping in)

Moreover, different equations are used in straight and curved sections.

5.2.3.2 Torque and drag in a straight section

When we take into consideration drag values in a straight section, then the Coulomb friction model should be used. The force used for moving the element is defined by:

(10) $\Delta F = \beta w \Delta L (\cos\alpha \pm \mu \sin\alpha)$

Where:

ΔF – force required to move the element [lb]

β – buoyancy factor [-]

w – unit weight element [lb/ft]

ΔL – length between survey points [ft]

α – inclination [°]

μ – friction coefficient [-]

First term of the above-mentioned equation - $\beta w \Delta L \cos\alpha$ - refers to the weight of the element, when the second part - $\beta w \Delta L \mu \sin\alpha$ - relates to additional friction force that is required to move the element.

Signs define following operations:

Sign	Type of the operation
+	Pulling out
-	Tripping in

Tab. 10. Signs defining chosen types of operations

Moreover, when:

- $\alpha = 0°$ then it indicates that pipe is in absolutely vertical position and friction can be diminished.

- $\alpha = 90°$ then it means that pipe is in horizontal position and weigh will be diminished.

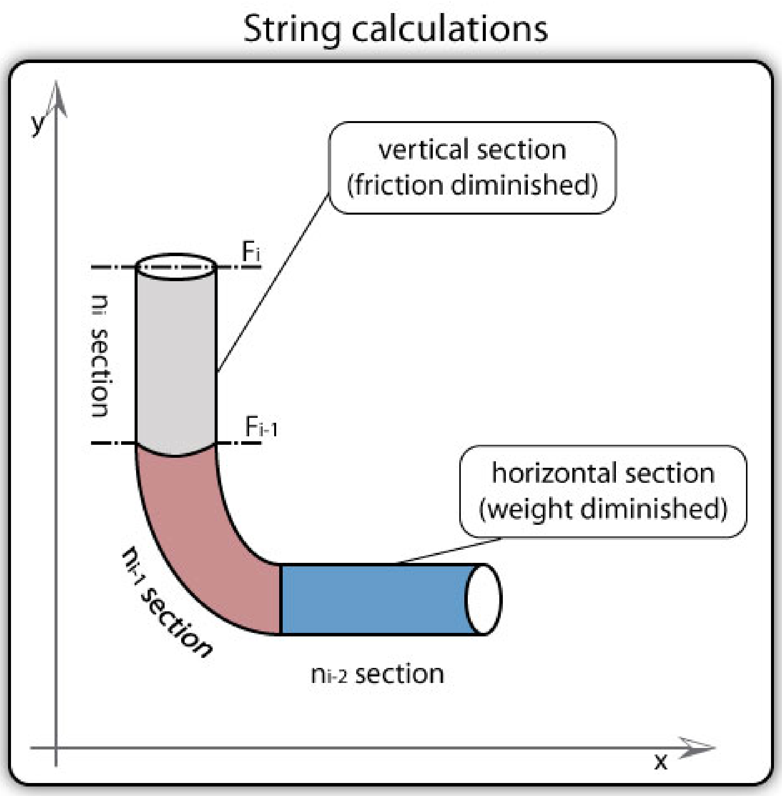


Fig. 19. String calculations

All the calculations are done from the bottom of the string, into direction of the surface (top of the string). The same approach is used for straight, as well as curved sections.

The whole string is divided in n-elements, where F_{i-1} is the element at the bottom of the chosen section and F_i is the element at the top of the section.

The following equations are used for calculating different values in the straight section consisting of n-elements:

Serial number	Value to be calculated	Derived equation
(11)	Hook load [lbs]	$\sum_{i=2}^{n} F_i = \sum_{i=2}^{n} F_{i-1} + \sum_{i=2}^{n} \{\beta w \Delta L(\cos\alpha \pm \mu \sin\alpha\}$
(12)	Drag force [lbs]	$\sum_{i=2}^{n} F_i = \sum_{i=2}^{n} F_{i-1} + \sum_{i=2}^{n} \{\pm \beta w \Delta L \mu \sin\alpha\}$
(13)	Torque [ft·lb]	$\sum_{i=2}^{n} T_i = \sum_{i=2}^{n} T_{i-1} + \sum_{i=2}^{n} \{\mu \beta w \Delta L r \sin\alpha\}$

Tab. 11. Equations used for calculating different values in the straight section consisting of n-elements

It has to be mentioned that when It refers to the last equation (torque), a straight section may consist of different tool joint radii. That is why it should be taken into special consideration.

5.2.3.3 Torque and drag in a curved section

Taking into consideration torque and drag in curved sections, it has to be assumed that the pipe is weightless when calculating friction, however, the weight is added at the end of the bend.

Moreover, in the case (curved boreholes), '(...) normal contact force between string and hole is strongly dependent on the axial pipe loading (...)'.

The 3-D model differs from 2-D one, especially with one additional input value. In the first case, we consider both inclination and azimuth, when in the second one, just inclination. That is why, there has to be included one more unknown value in the calculations, called – dogleg angle θ - that depends both on, mentioned-above, the inclination and the azimuth.

Furthermore, the pipe in the model, as well as in real conditions, contacts either low side or high side of the curved wellbore, thus the surface is defined as the dogleg plane.

The following equations are used for calculating different values in the curved section consisting of n-elements:

Serial number	Value to be calculated	Derived equation
(14)	Dogleg angle [rad]	$\cos\vartheta_i = \sin\alpha_i \sin\alpha_{i-1}\cos(\phi_i - \phi_{i-1}) + \cos\alpha_i \cos\alpha_{i-1}$
(15)	Hook load [lbs]	$\sum_{i=2}^{n} F_i = \sum_{i=2}^{n}\left[F_{i-1}\cdot e^{\pm u_i\lvert\vartheta_i\rvert}\right] + \sum_{i=2}^{n}\left\{\beta_i w_i \Delta L_i \cdot \left[\frac{\sin\alpha_i - \sin\alpha_{i-1}}{\alpha_i - \alpha_{i-1}}\right]\right\}$
(16)	Drag force [lbs]	$\sum_{i=2}^{n} F_i = \sum_{i=2}^{n}\left[F_{i-1}\cdot e^{\pm u_i\lvert\vartheta_i\rvert}\right]$
(17)	Torque [ft·lb]	$\sum_{i=2}^{n} T_i = \sum_{i=2}^{n} u_i \cdot r_i F_{i-1}\lvert\vartheta_i - \vartheta_{i-1}\rvert$

Tab. 12. Equations used for calculating different values in the curved section consisting of n-elements

All in all, all the values can be computed by dividing the whole length of the well into straight and curved sections. Hook load, drag and torque forces are added from the bottom of the well, to the top. The final result is based on especially on well geometry and pipe sizes. The influence of the factors is shown in other sub-chapters.

5.3 Directional profile

Directional profile, in defiance of others opinions, has really marginal influence on torque and drag issues.

To prove the above thesis, calculations have been done regarding relationships between:
- hook load and various directional profiles
- hook load and inclination while tripping out
- hook load and inclination while tripping in
- rotary torque and inclination

However, there will have to be filled some unknowns and made some calculations, as following:
- Kick-Off-Point
- target TVD
- horizontal displacement
- build rate
- final inclination
- friction coefficient
- hook load (while: trip in, trip out)
- pipe tension (while: trip in, trip out)
- rotary torque

It should be noted that directional profile makes very small difference in the total drag, in relate to other issues. Moreover, it can be seen that the most important factors determining value of the drag are horizontal displacement and TVD. However, when dealing with complicated well patterns, especially in Extended Reach Drilling wells, directional profile can be more significant.

5.4 String weight

5.4.1 Overview

Next factor that has influence on and reduce torque and drag in directional wells is string weight. The basic goal is to reduce compression or tension in the drill string.

In most of the deviated and directional wells, pipes are in tension, while tripping in or out, in most of the doglegs. However, especially in Extended Reach Drilling wells, pipes are mostly in compression while tripping in and conversely – in tension while tripping out.

Use of drill string components responsible for Weight-On-Bit affects the weight significantly. For example, when we consider horizontal drilling, 6 ¼" drill collars are often used with 8 ½" holes, with DLSs (dogleg severity) between $10°/100$ ft to $15°/100$ ft, while non-rotating.

On the weight indicator usually no drag is seen while entering the build curve, by the drill collars.

When it relates to drill pipes, the situation is even simpler. They are more flexible and experience less drag in build-up or drop-down sections. So, there have to influence large forces (tension or compression) while going throw curvature to see significant change in drag values.

So, we can simply conclude that with increase of the tension in curved section, the value of the drag will also increase. And conversely, decrease of tension in the section, will work with reduced torque & drag values.

However, there are of course methods of reducing a drill string tension, for example, minimizing the amount of collars. Nevertheless, other factors have to be considered, because of the fact that drill collars are responsible for string stiffness while directional drilling and moreover for providing Weight-On-Bit, especially in deflected wellbores.

All in all, with some exceptions, no more than three collars are required.

Heavy-Weight Drill Pipes can be utilized as a substitute of drill collars. They are lighter than them, thus, they can reduce total drill string weight beneath curved section. Moreover, for the sake of greater stiffness, lower size pipes can be utilized.

Typical HWDP (Heavy-Weight Drill Pipes) can be found in the table below.

Nominal OD [in.]	ID [in.]	Tool joint OD [in.]	Center upset OD [in.]	Weight per foot with tool joint [in.]
3 ½	2,0625	4,75	4,00	25,30
4	2,5625	5,25	4,50	29,70
4 ½	2,7500	6,25	5,00	41,00
5	3,0000	6,50	5,50	49,30

Tab. 13. Typical Heavy-Weight Drill Pipes

Another aspect that affects string weight is material of utilized drill pipes.
Each of the materials shown in 'Detailed selection of drill pipes' chapter, has its adequate properties, also regarding weight. Also each of them can significantly reduce weight or other physical concerns, thereby reducing, or at least keeping the same overall cost.

Examples of commercial drill pipes made of three different materials are shown below:

	Pipe body			Tool join			Assembly weight [kg/m]
	Material	ID [in.]	OD [in.]	Material	ID [in.]	OD [in.]	
Steel Drill Pipe	S-135	4,27	5,00	Steel	3,50	7,25	35,30
Aluminum Drill Pipe (steel TJ)	Al-Cu-Mg	4,21	5,00	Steel	3,70	6,25	15,10
Titanium Drill Pipe (steel TJ)	Composite (e-glass / graphite / epoxy)	5,00	6,00	Steel	5,00	7,00	18,60

Tab. 14. Commercial drill pipes made of different materials

It must be noted how much Steel Drill Pipes are heavier than analogous Aluminum Drill Pipes or even Titanium Drill Pipes. On the current level of the analyze, excepting cost-efficiency, weight properties of alloy pipes are crushingly better than steel pipes. Extended tests and calculations will be shown in the next chapter.

5.4.2 Calculation

Furthermore, calculations have been done to show how different types of pipes affect overall weight of the drill string. Input values have been used:

- build-up rate
- maximum inclination
- Kick-Off-Point
- drill collars (number and weight)
- Bottom Hole Assembly

as well as assumption regarding well pattern.

As an output, hook load value, without top drive, has been calculated.

Comparison of individual results has been presented on the graph.

5.5 Buckling evaluation

5.5.1 Overview

Buckling of pipes is another important factor affecting drilling performance in the petroleum industry. Generally, long and slender pipes are in use that can be easily buckled under influence of external forces.

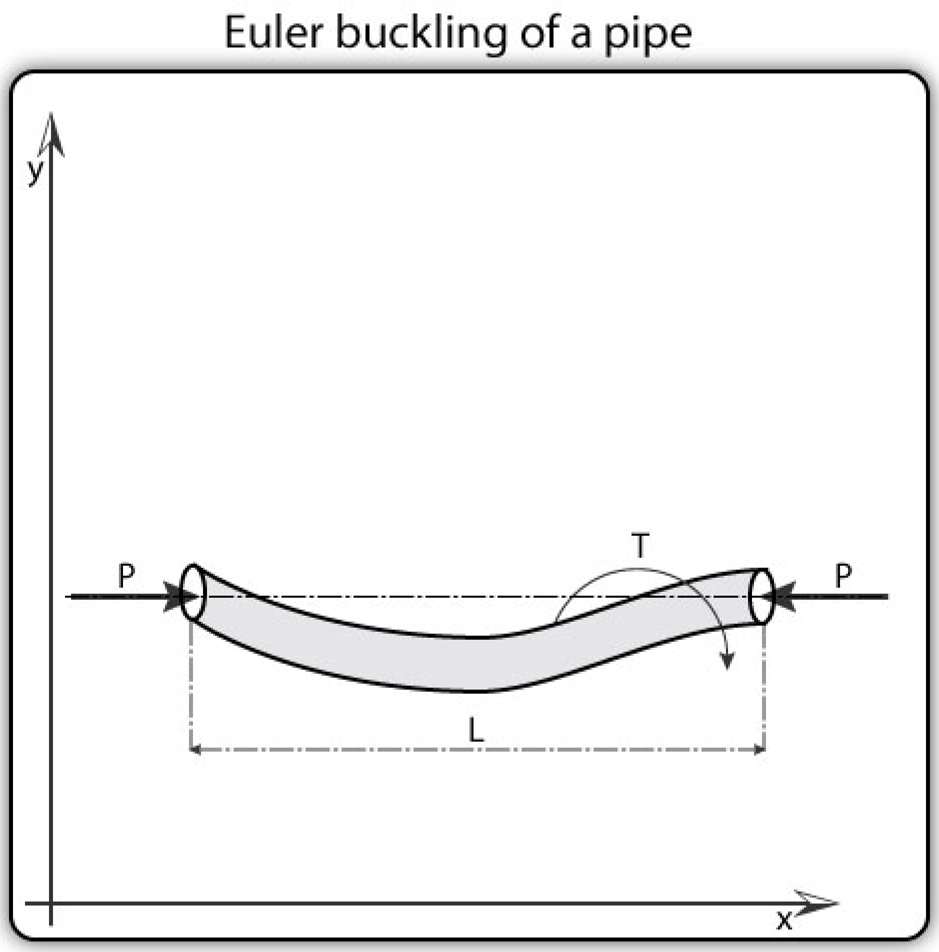


Fig. 20. Euler buckling of a pipe

It is easy to predict what can happen then. For example, a pipe can lock due to creation of side-forces at contact points. Moreover, pipes can lose their stiffness and it is impossible to provide required Weight-On-Bit. It matters, especially while drilling strongly deviated or horizontal wells. Other negative results are difficulties in transferring torque or upset hydraulics. It becomes even more important nowadays because forces requirements are much higher than years ago.

However, in the master thesis just sinusoidal buckling is considered, because of the complexity in calculations of helical one.

5.5.2 Basic model

When it comes to buckling calculations, the most elementary solution refers to Euler's one. Due to the shape of the model, external bending moment is balanced by internal strain moment. The critical force equation, which derives from classical beam theory, looks as follows:

$$P_{cr} = EI\frac{\pi^2}{L^2} \quad (1)$$

Where:

P_{cr} - critical force that initiates buckling

E - Young's modulus

I - moment of inertia

L - pipe length

Supposing idealized tubular model, supported at each end, the critical axial force that initiates buckling is defined by above-mentioned equation. However, if at least one of the ends is fixed, then another, modified equation is applicable.

Two buckling models are distinguished:
- buckling on laterally supported tubular
- buckling in curved boreholes and torsion

5.5.3 Buckling on laterally supported tubular

To calculate buckling, while taking into consideration such factors as pipe weight and inclination, a more advanced equation has been derived by Dawson, Pasley and Bogy:

$$P_{cr} = EI\frac{\pi^2}{L^2}\left(n^2 + \frac{L^4 w \sin\vartheta}{n^2\pi^4 EIr}\right)$$ (2)

Where:

n - order of buckling [-]

w - buoyed pipe weight

ϑ - inclination of the pipe $[°]$

r - radial clearance between a pipe and a hole

The final version of the above-mentioned equation, which considers determination of the buckling order and is commonly in use, looks as follows:

$$P_{cr} = 2\sqrt{\frac{EIw\sin\vartheta}{r}}$$ (3)

However, it has to be mentioned that there are some significant differences between Euler's model and Dawson-Pasley-Bogy. First and foremost, in the first case it has been assumed that the pipe is absolutely unsupported, whereas in the second one, the pipe is supported sideways along the whole length.

There is a fundamental difference in application of both of the models, as well. Euler's model can be used when there are short distances between pivot points and conversely – Dawson-Pasley-Bogy model should be used for longer distances.

When a pipe is taken as an example, values resulted from both of the models are equal, just when the length of the pipe is 5,2m. For longer tubular, Dawson-Pasley-Bogy model will have to be used.

All in all, the second of above-mentioned models is generally in use.

5.5.4 Buckling in curved boreholes and torsion

The main model that has been used is Dawson-Pasley-Bogy. However, there are other conditions, which have practical application.

The first one is developed by Kyllingstad, which has practical application in sinusoidal, as well as helical buckling:

(4) $$P_{cr} = \sqrt{\frac{KEIf_o}{r}}$$

Where:

K - a factor determining type of buckling

f_o - normal force that takes into account wellbore curvature

If:

$K = 4 - 12{,}25$ than it is applicable to sinusoidal buckling

$K = 8 - 7{,}5$ than it is applicable to helical buckling

Moreover, there has been carried out a model that took into consideration simultaneous axial load and torque. As the result, it was concluded that critical buckling load was lower than torque. Furthermore, the relationship between torque-less solution and torque-used one was defined by:

(5) $$P_{cr} = P_{cr}(1 - 0{,}42r)$$

When no axial loads are applied and just torque influence is considered, than the pipe can buckle as well, according to:

(6) $$T_{cr} = 2{,}09\sqrt[4]{\frac{(EI)^3 f_o}{r}}$$

5.5.5 Graphical interpretations

Graphical interpretations of sinusoidal (a) and helical (b) buckling:

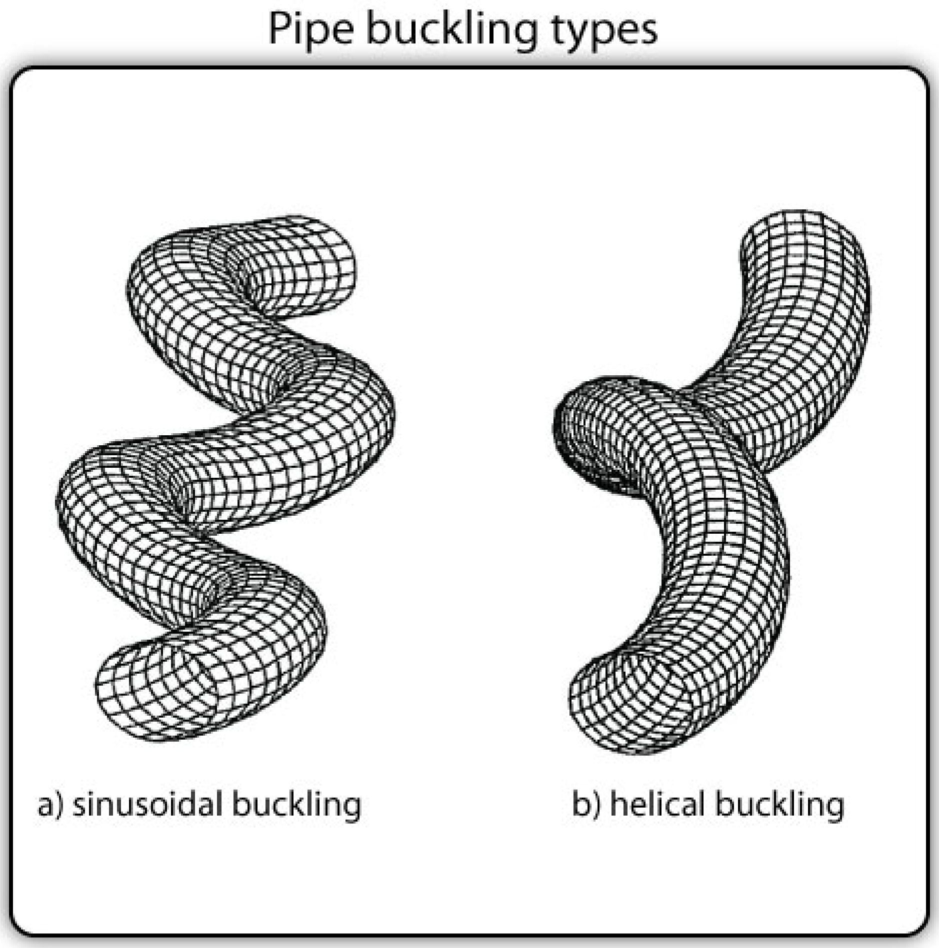


Fig. 21. Pipe buckling types

5.6 Friction coefficient

5.6.1 Overview

Friction coefficient and pipe normal force are factors that determine the drag significantly. For example when friction coefficient is reduced by half than the drag will be reduced by half as well.

There are some factors that have huge influence on the friction coefficient.

First and foremost they are:

- mud type
- bentonite content
- solids content
- various additives in the mud

Generally, we can say that the highest friction coefficient belongs to dry air and water-base muds, when the lowest one to oil-based muds. Moreover, higher values occur in open hole sections than in cased segments.

However, to all of the statements above, two fundamental assumptions have to be done:

- the hole is absolutely clean
- no differential sticking occurs

Common friction coefficient values for different types of mud and for two cases are shown below:

Mud type	μ in casing	μ in formation
Oil- or Synthetic-Based Mud	0,15 to 0,20	0,17 to 0,25
Water-Based Mud	0,25 to 0,35	0,25 to 0,40
Brine	0,30 to 0,40	0,30 to 0,40
Air and Mist	0,40 to 0,50	0,40 to 0,50

Tab. 15. Common friction coefficient values for different types of mud

5.6.2 Calculation

Influence of friction coefficient, based on torque and drag model, has been calculated. As input values following unknowns have been used:

- Kick-Off-Point
- dogleg severity (DLS)
- inclination
- Measured Depth
- Horizontal Departure
- weight of the string
- friction coefficient

as well as assumptions regarding well pattern and mud type.

As an output hook loads for given conditions have been calculated.

Comparison of individual results has been presented on the graph.

5.7 BHA design

5.7.1 Overview

Another and last factor in the thesis affecting drilling performance is Bottom-Hole-Assembly design. Main functions of the BHA are:

- provide force on the bit
- ensure efficient drilling process

Typical BHA consists of (from the bottom to the top):

- drill bit
- MWD/LWD
- stabilizer
- drill collars
- jar
- Heavy-Weight Drill Pipes
- Drill pipes

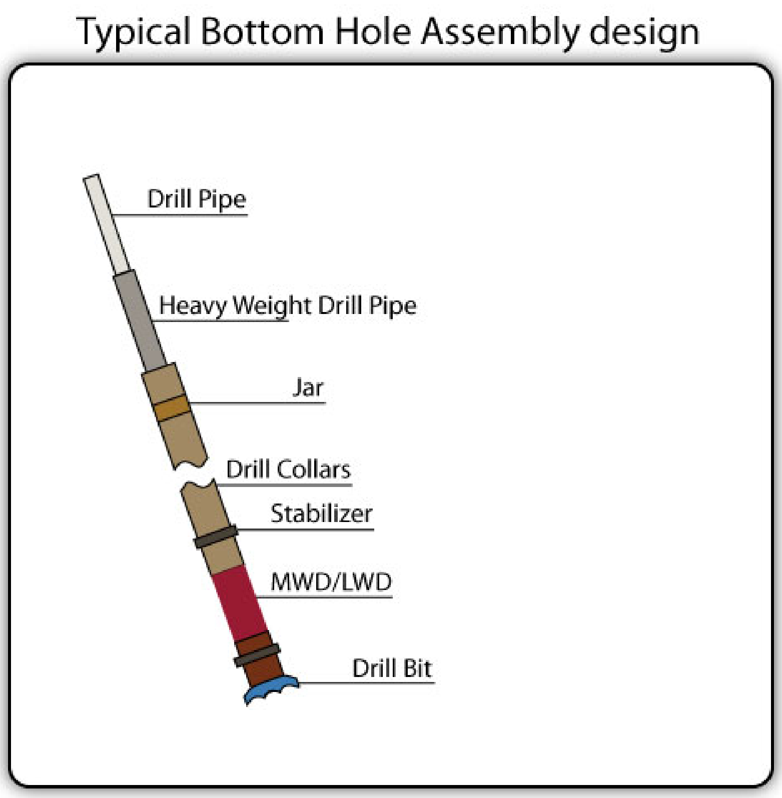


Fig. 22. Typical Bottom Hole Assembly design

However, it might be changed according to conditions and given requirements.

Another aspect when it refers to BHA design is actual condition of the assembly. In practice it means, whether it is in partial or in total compression. The ‘neutral point’ is the place where effective string force goes from tension to compression.
An old practice used to define the neutral point in 2/3 length from the bit, however nowadays it is common to have the complete BHA in compression.
Furthermore, the most common aspect – friction coefficient must be included in the analyze.
And finally, buoyancy factor of pipe weight should be presented, as following:

(1) $$\beta = 1 - \frac{\varphi_{mud}}{\varphi_{pipe}}$$

Where:
β - pipes buoyancy factor
φ_{mud} - mud density
φ_{pipe} - pipe density

Then, we have to make some assumptions:
- define maximum hole inclination
- determine the work mode (rotary vs. sliding)

After selecting sliding mode for the drill string, it is clarified that friction is comprehended as an axial drag. Thus the total length of the BHA is:

(2) $$L_{BHA} = L_{BHA1} + L_{BHA2}$$

Also the resistance towards axial motion is given by well-known equation:

(3) $$F_{friction} = \mu W \sin \alpha$$

And, the total weight of the BHA equals to:

(4) $W = \beta w L_{BHA}$

Where:

w - unit weight

L_{BHA} - BHA length

Thus, the string stops to slide, when the weight equals the friction:

(5) $\beta w L_{BHA} \cos\alpha = \mu \beta w L_{BHA} \sin\alpha$

5.7.2 Drilling assembly vs. working mode

For motor drilling, including correction runs with bent sub, in a non-rotating mode, the axial drag has to be included. Thus, the length of the BHA is determined by:

(6) $L_{BHA} = \dfrac{F_{bit}}{\beta w(\cos\alpha - \mu \sin\alpha)} + L_2$

For rotary drilling, the axial drag can be neglected, thereby the total length of the BHA is as following:

(7) $L_{BHA} = \dfrac{F_{bit}}{\beta w \cos\alpha} + L_{BHA2}$

With above-mentioned equations, the length of the BHA can be determined. However, when we assume that L_{BHA2} is a pre-defined fraction of L_{BHA1}, than from the relationship between the values ($K = \dfrac{L_{BHA2}}{L_{BHA1}}$), we can modify foregoing equations to:

- for the 1st case (non-rotating):

(8) $$L_{BHA} = (1+K)\frac{F_{bit}}{\beta w(\cos\alpha - \mu\sin\alpha)}$$

- for the 2nd case (rotating):

(9) $$L_{BHA} = (1+K)\frac{F_{bit}}{\beta w\cos\alpha}$$

5.7.3 Highly deviated wells

Drilling vertical or slightly deviated wells is gravity-based process. It means that force to the bit is transferred especially thanks to gravity influence.

However, it is common nowadays to drill highly deviated or even horizontal wells. The key to achieve desirable drilling performance in such wells is to place drill collars in a downward dip to provide force. As it is shown at the illustration below, the force is transferred through a bend to the bottom w a BHA.

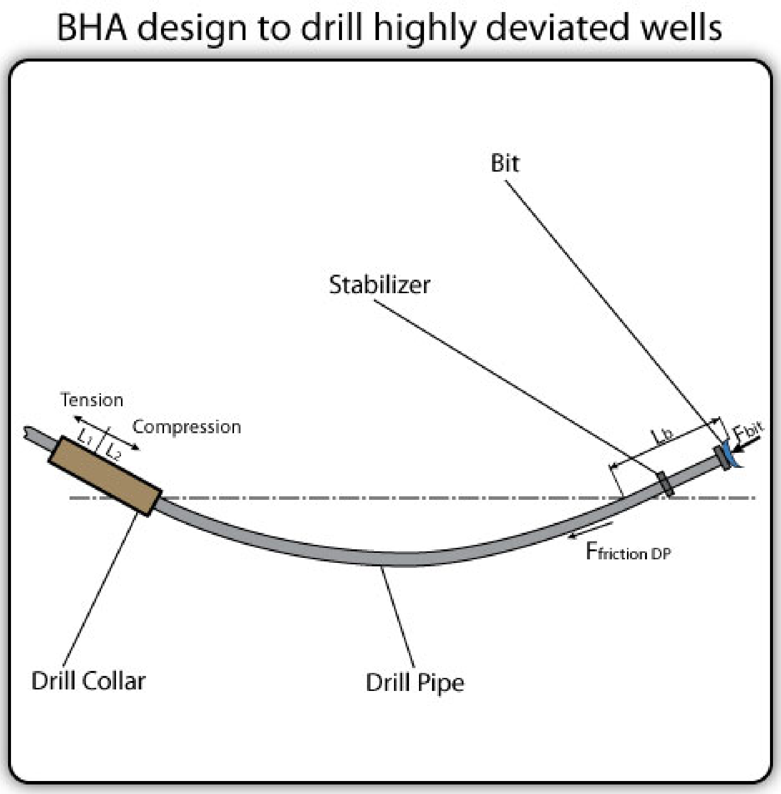


Fig. 23. BHA design to drill highly deviated wells

Assuming that w_1 is the weight unit of the drill collars and similarly w_2 is the weight unit of the drill pipes, and friction coefficient for the units has the same index, a force balance (along the axis, starting from neutral point) is defined by:

(10) $$\beta w_1 L_{BHA1} \cos\alpha - F_{friction-1} - F_{friction-2} - \beta w_2 H_{TVD} = F_{bit}$$

Then, when above equation for drill collars friction: $\beta w_1 L_{BHA1} \cos\alpha - F_{friction-1}$ is inserted into equation (8) for non-rotating case, then the length of drill collars in the BHA will be obtained:

(11) $$L_{BHA} = (1+K)\frac{F_{bit} + F_{friction-2} + \beta w_2 H_{TVD}}{\beta w_1 (\cos\alpha - \mu \sin\alpha)}$$

The last equation in the sub-chapter refers to the same length as in equation (11), however in rotational mode, so the axial friction is neglected, as follows:

(12) $$L_{BHA} = (1+K)\frac{F_{bit} + \beta w_2 H_{TVD}}{\beta w_1 \cos\alpha}$$

6. Calculation results

6.1 Fatigue resistance

6.1.1 Introduction to results and observations

Three different materials have been taken into consideration:

- steel
- aluminum
- composite

Observations that are worth mentioning:

- no laboratory tests have been performed on the materials
- just theoretical assumptions have been done
- based on available data, S-N curves have been created for different materials, as below:

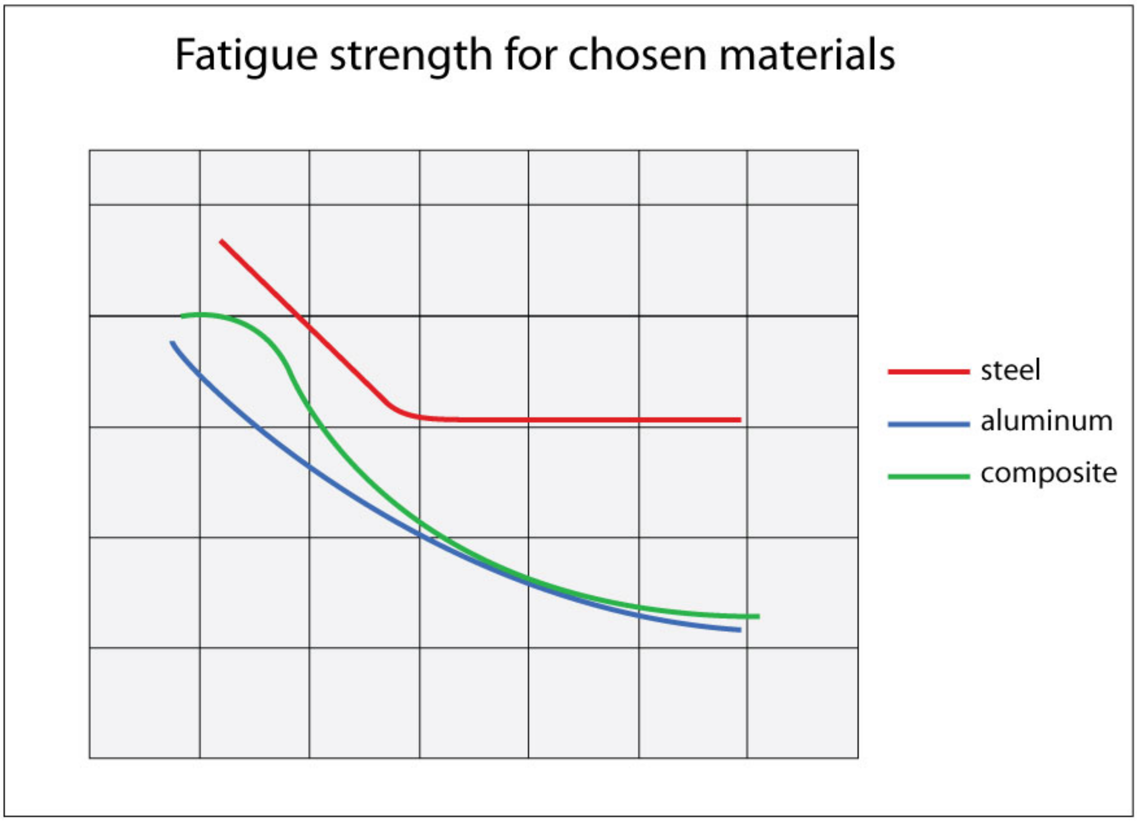


Fig. 24. Fatigue strength for chosen materials

Following properties have been observed

steel curve:

- material with the highest endurance limit
- can withstand the largest loadings
- has constant resistance on the lowest level

aluminum curve:

- the weakest material in the breakdown
- constantly reduced fatigue strength

composite curve:

- material with moderate endurance
- can withstand large load in the beginning
- significant decrease of fatigue resistance level

6.1.2 Conclusion

In the chapter, just fatigue resistance is taken into consideration. Thereby, steel pipe is the best solution, for the sake of:

- the greatest fatigue strength
- constant endurance limit
- possibility of carrying the highest changeable loads

Second place belongs to composite pipes:

- better fatigue resistance than aluminum pipes
- can withstand higher changeable loads
- although the fatigue curve is changed in irregular manner with higher values of cyclic loads, it still remains better or at least equal to aluminum pipes

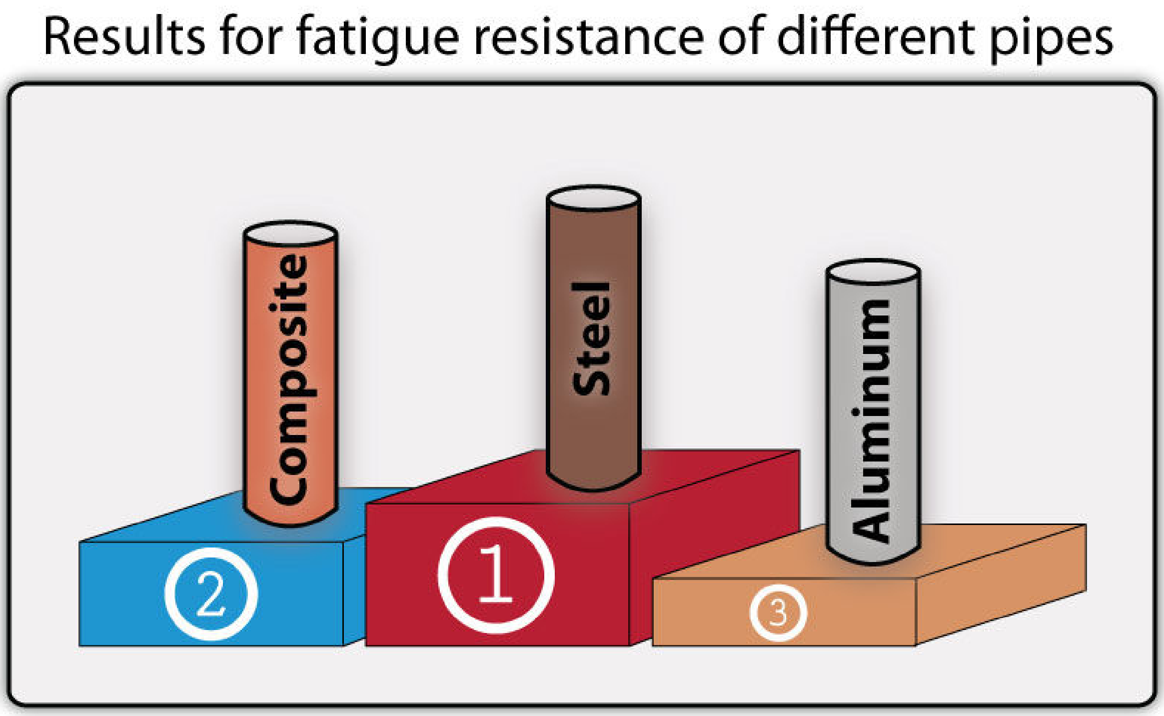


Fig. 25. Results for fatigue resistance of different pipes

6.2 Simplified torque & drag model

6.2.1 Introduction to results and observations

First, model conditions had to be established, as following:

Number	Factor	Value	Comments
1	Water Based Mud	10,2 [ppg]	Friction factor: 0,3 (cased hole section) 0,33 (open hole section)
2	S-135 drill pipes	22,6 [lb/ft]	Tool joint radius: 0,276 [ft]
3	Length between survey points	47,5 [ft]	-
4	Wellbore length	19.760 [ft]	-

Tab. 16. Model conditions for the conceptual well

Also two model condition states have been established:

- tripping out (POOH)

- tripping in (RIH)

In the model, for given condition states, following values are presented:

POOH:

Interval	Hook load [lbs]	Drag force [lbs]	Torque [ft·lb]
1,00	336 960,48	108 882,81	44 633,53

Tab. 17. Values of calculated variables of the conceptual well while POOH

RIH:

Interval	Hook load [lbs]	Drag force [lbs]	Torque [ft·lb]
1,00	93 399,89	63 100,96	22 840,85

Tab. 18. Values of calculated variables of the conceptual well while RIH

Comparison of hook loads, drag forces and torque while POOH and RIH is presented on next pages:

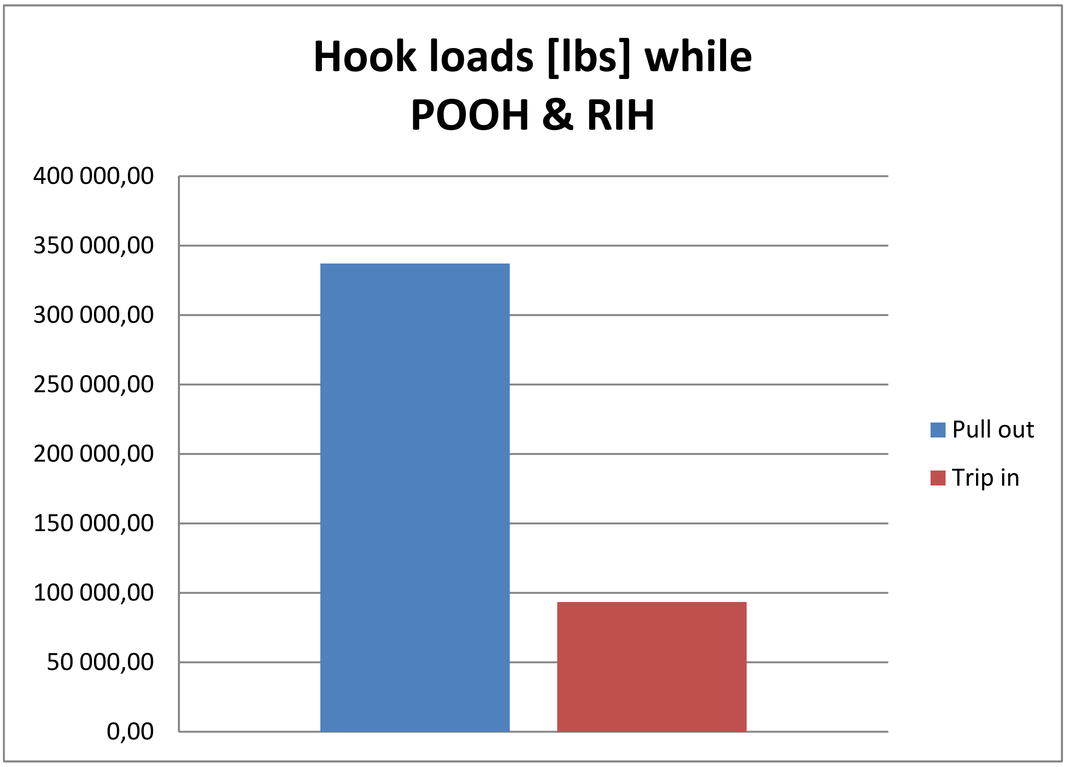


Fig. 26. Comparison of hook loads while POOH & RIH for the conceptual well

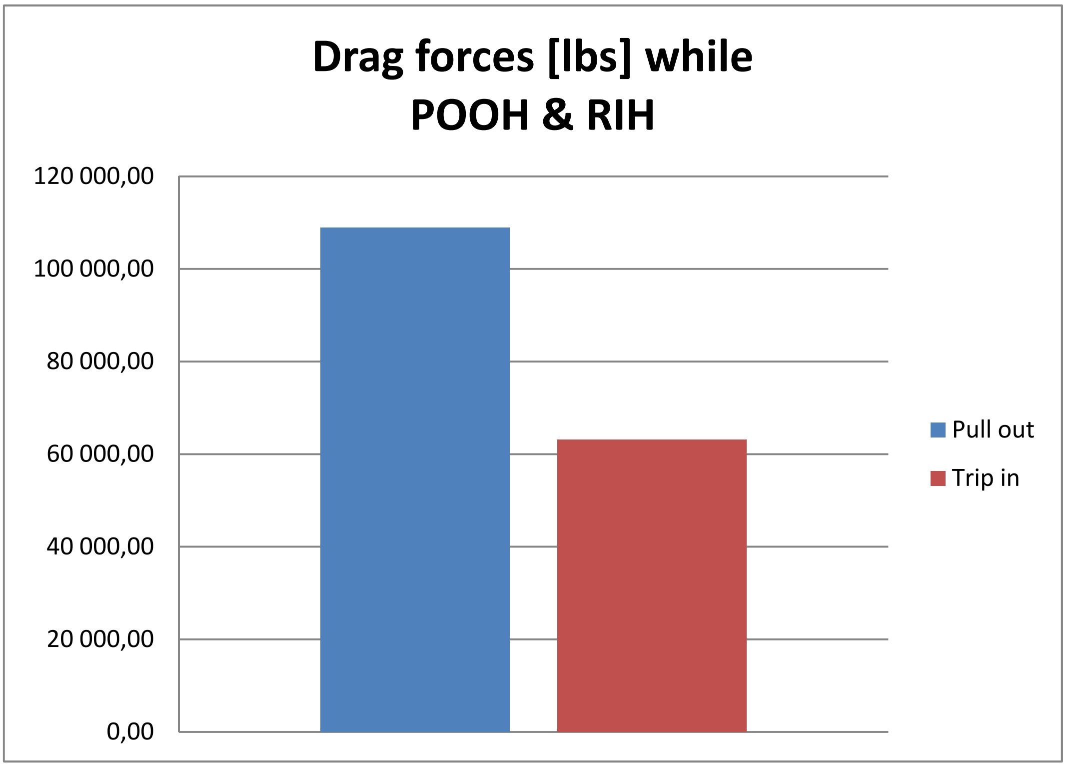


Fig. 27. Comparison of drag forces while POOH & RIH for the conceptual well

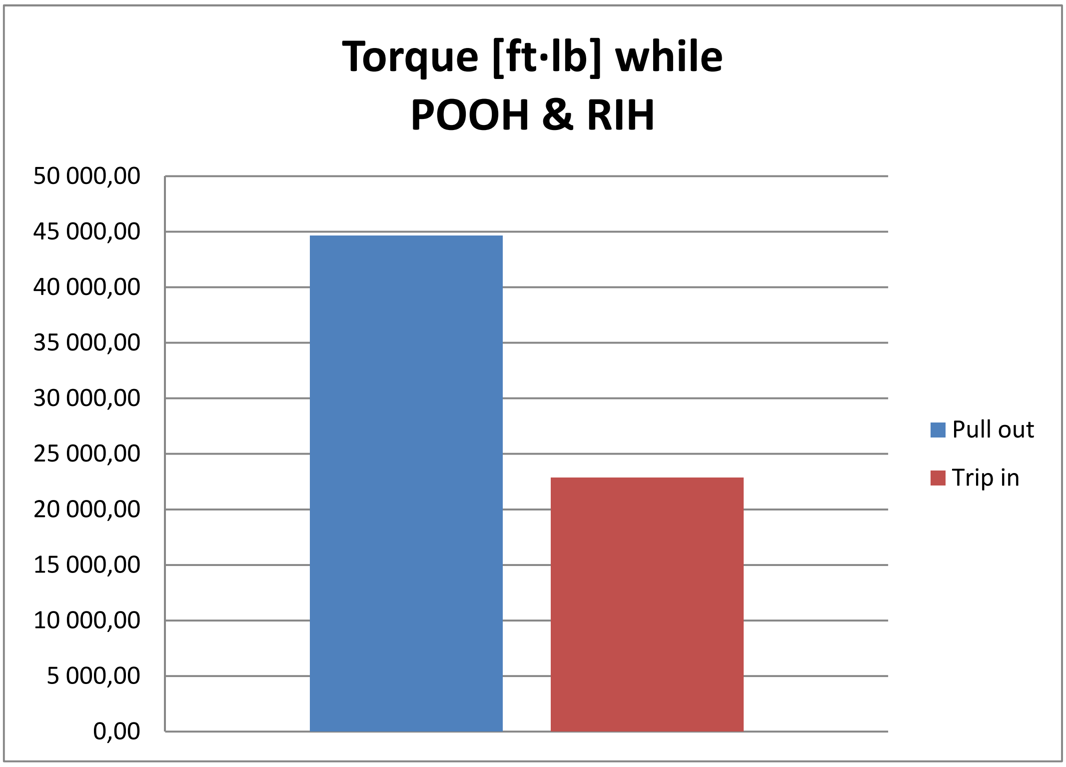


Fig. 29. Comparison of torque while POOH & RIH for the conceptual well

Moreover, hook load, drag force as well as torque are presented below as function of the calculated value and measured depth:

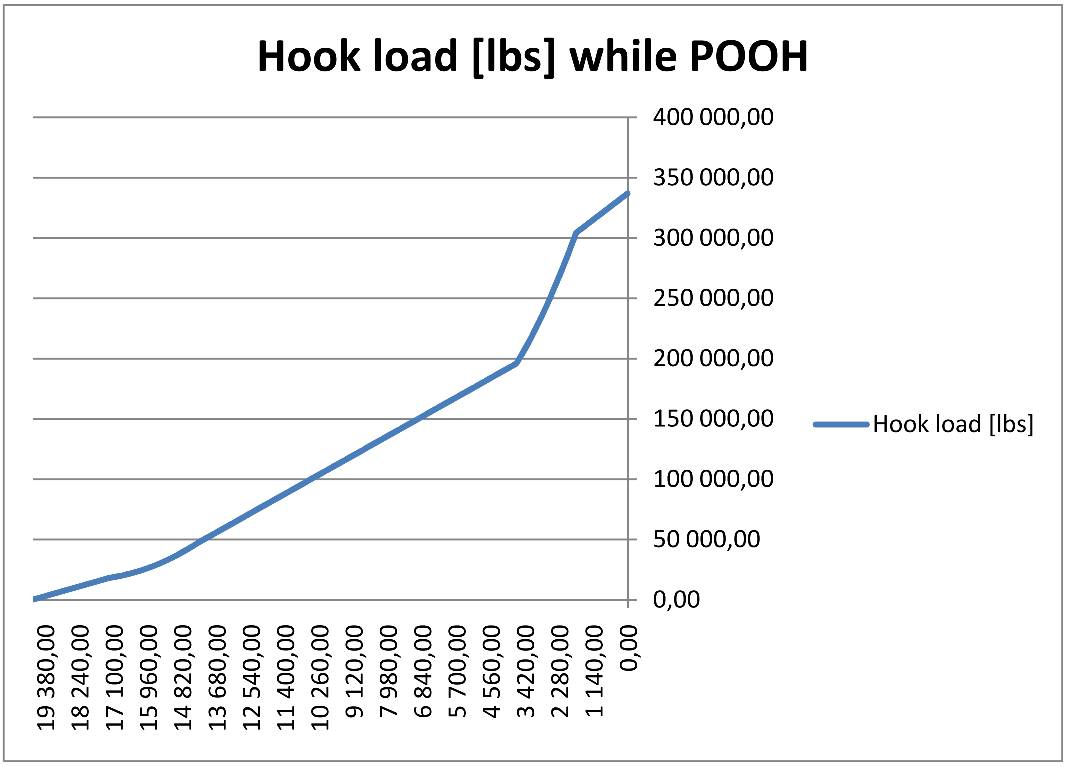


Fig. 28. Hook load as a function of calculated value and measured depth while POOH for the conceptual well

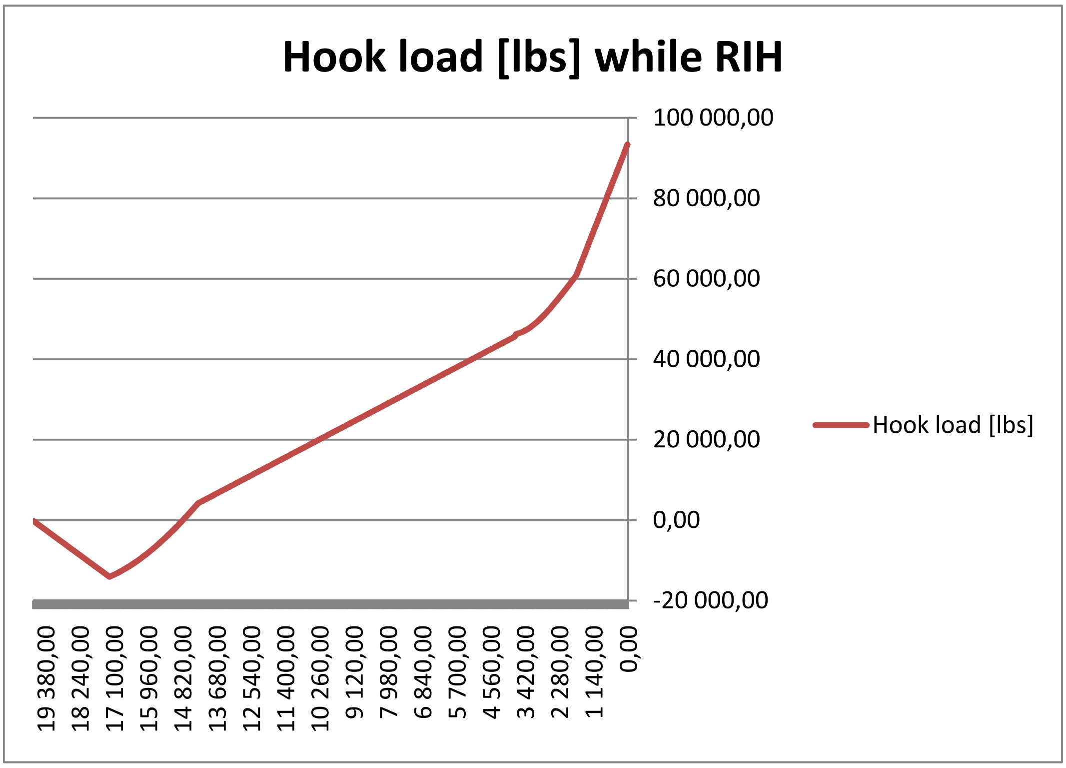


Fig. 30. Hook load as a function of calculated value and measured depth while RIH for the conceptual well

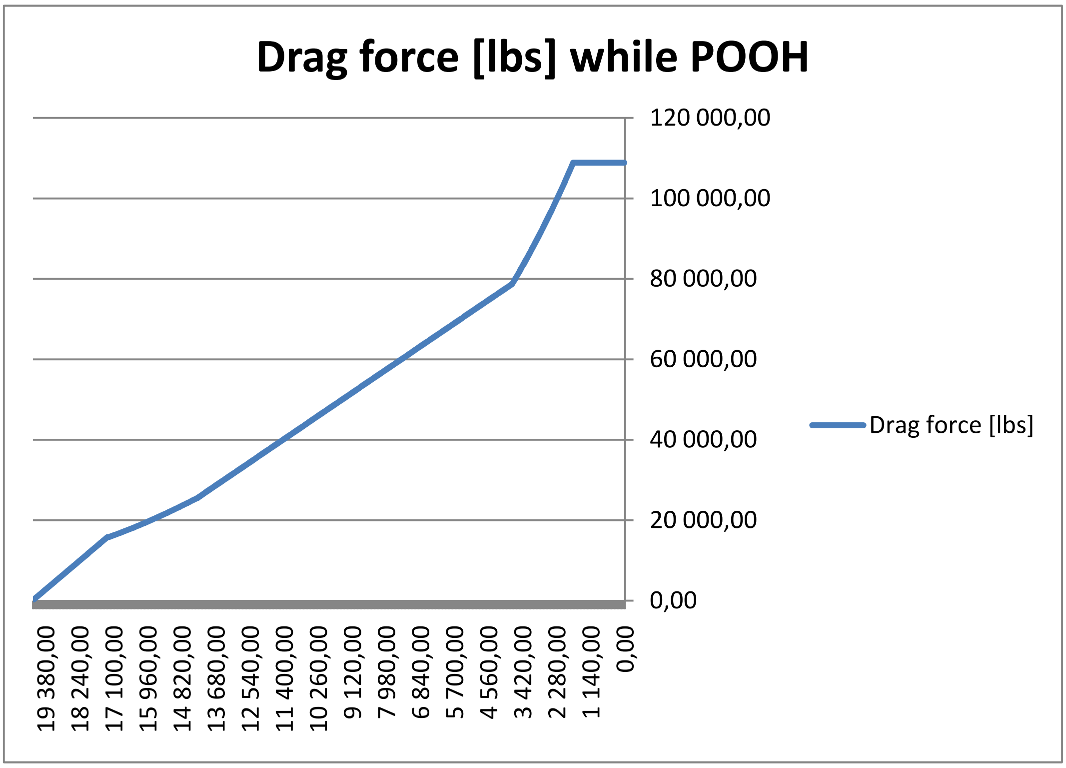


Fig. 31. Drag force as a function of calculated value and measured depth while POOH for the conceptual well

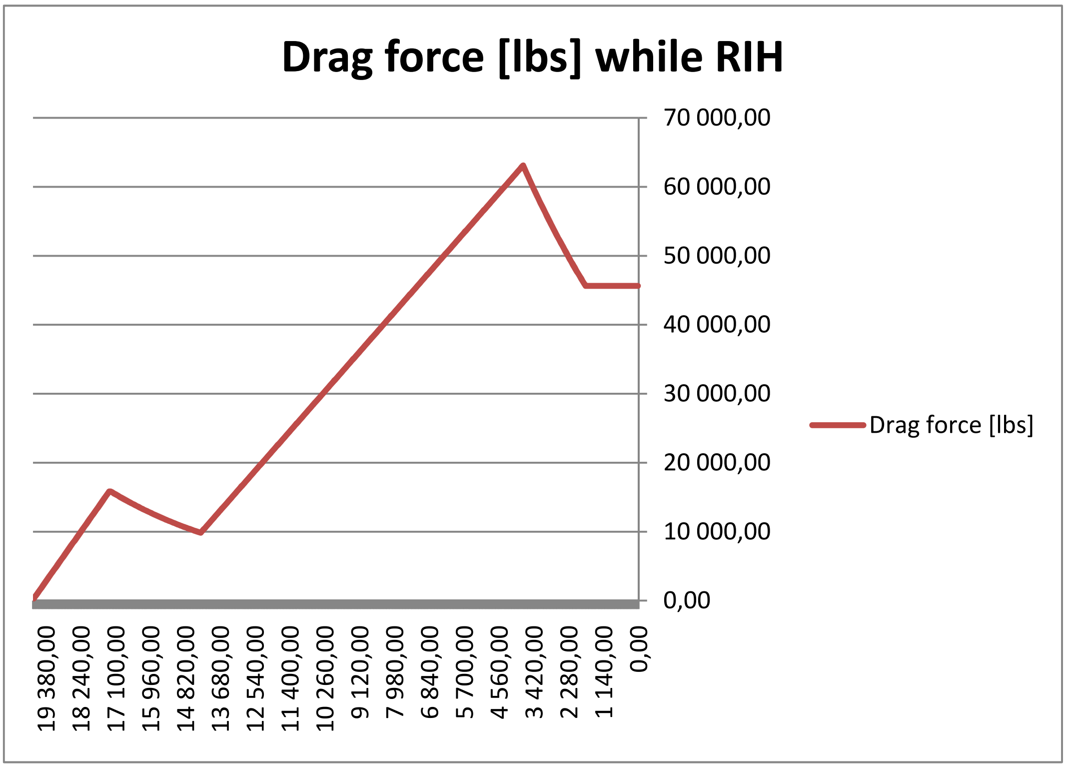


Fig. 32. Drag force as a function of calculated value and measured depth while RIH for the conceptual well

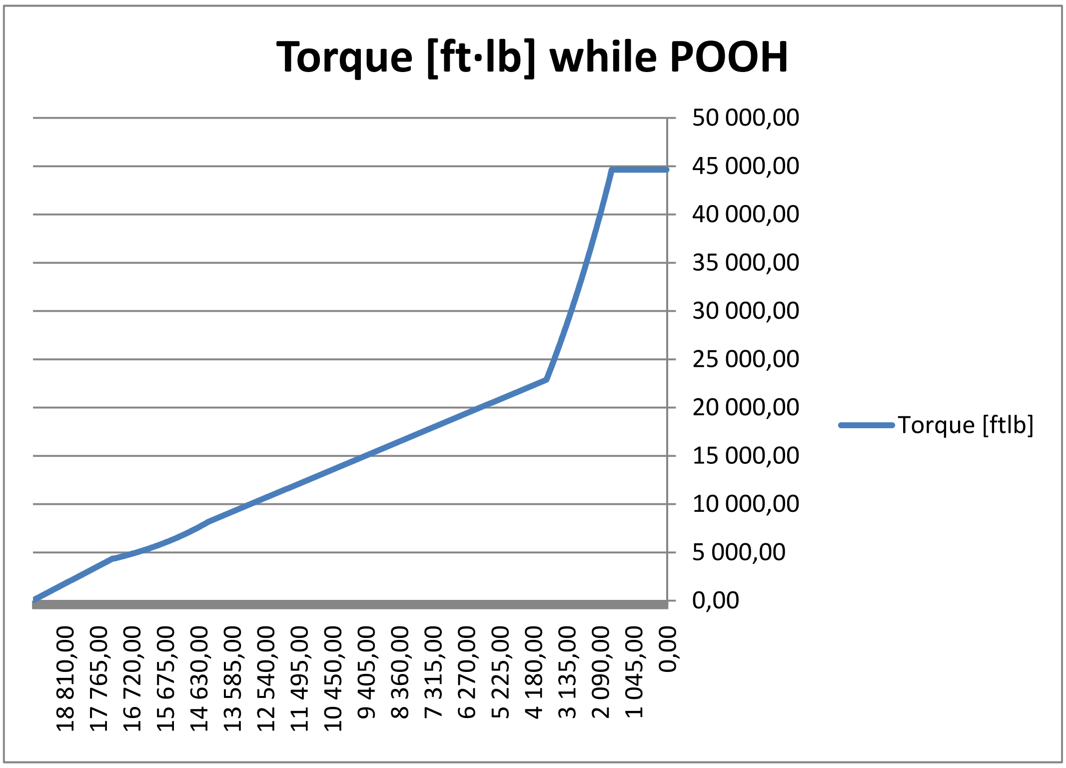


Fig. 33. Torque as a function of calculated value and measured depth while POOH for the conceptual well

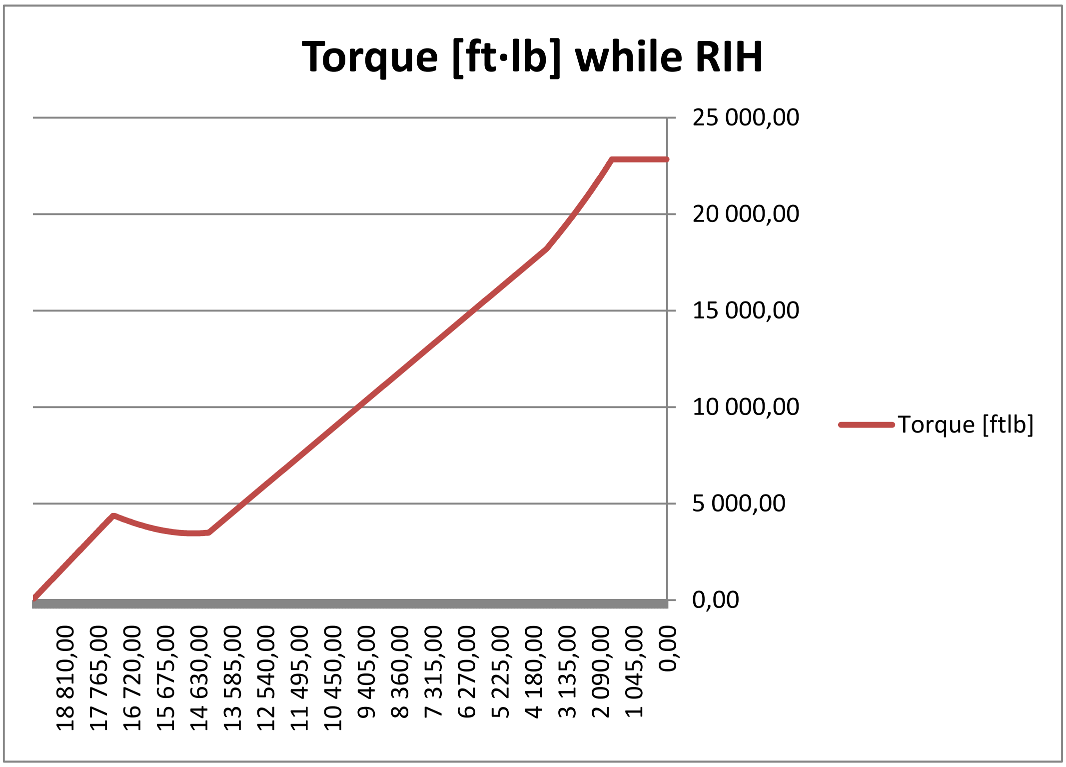


Fig. 34. Torque as a function of calculated value and measured depth while RIH for the conceptual well

It has to be noted that in some parts of the string, while tripping in, hook loads values are negative. It is caused by friction that is so huge in the given part of the wellbore that stops shifting of the string and release load at the hook.

Moreover, paradoxically the largest value of drag while tripping in is not at the surface (top of the 1st section), but at the Measured Depth of 3.752,5 ft. (top of the 3rd section).

Visual comparison of hook load, drag force and torque on the whole length of the well, while POOH and RIH is shown on next pages:

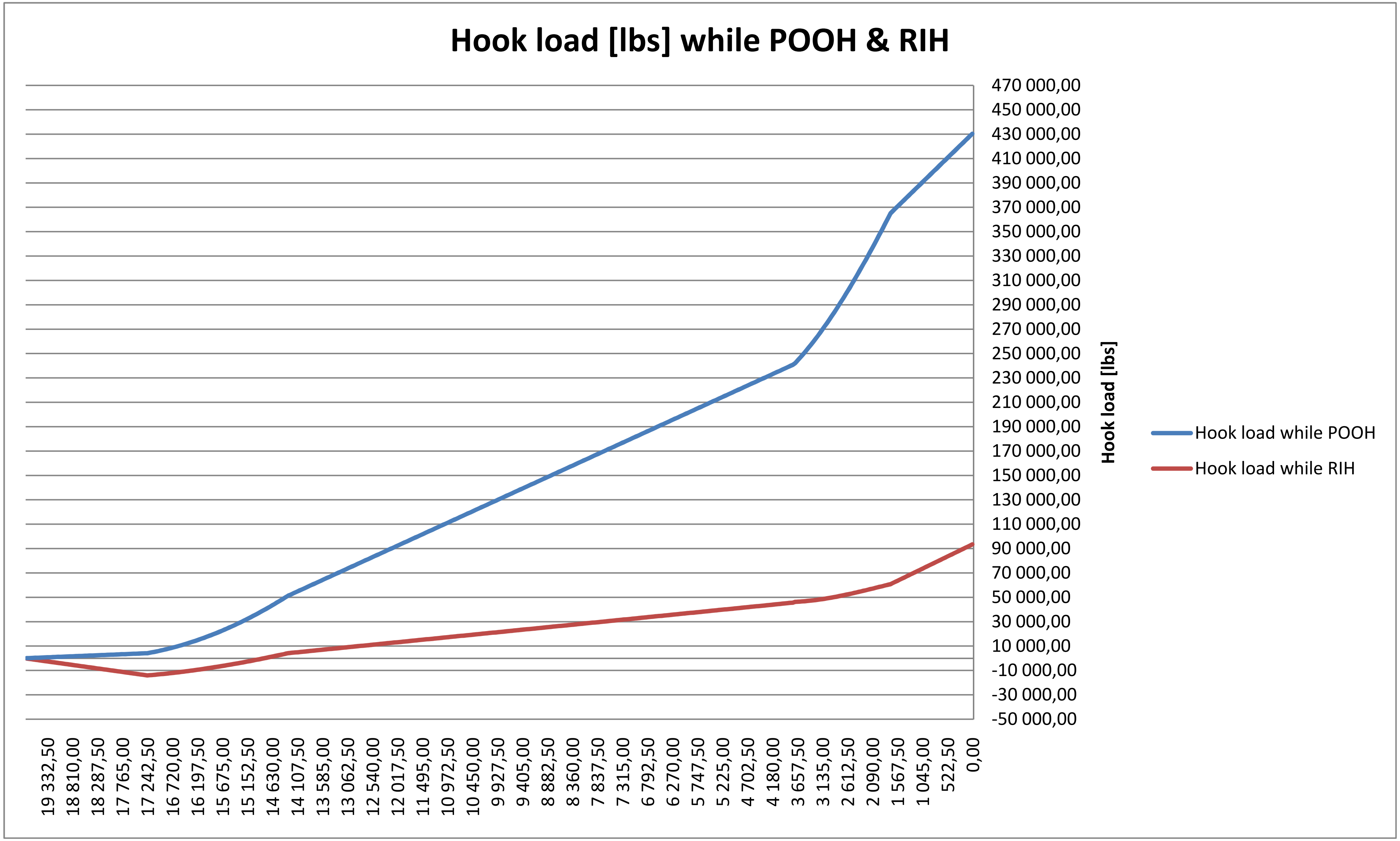


Fig. 35. Hook load comparison while POOH & RIH for the conceptual well

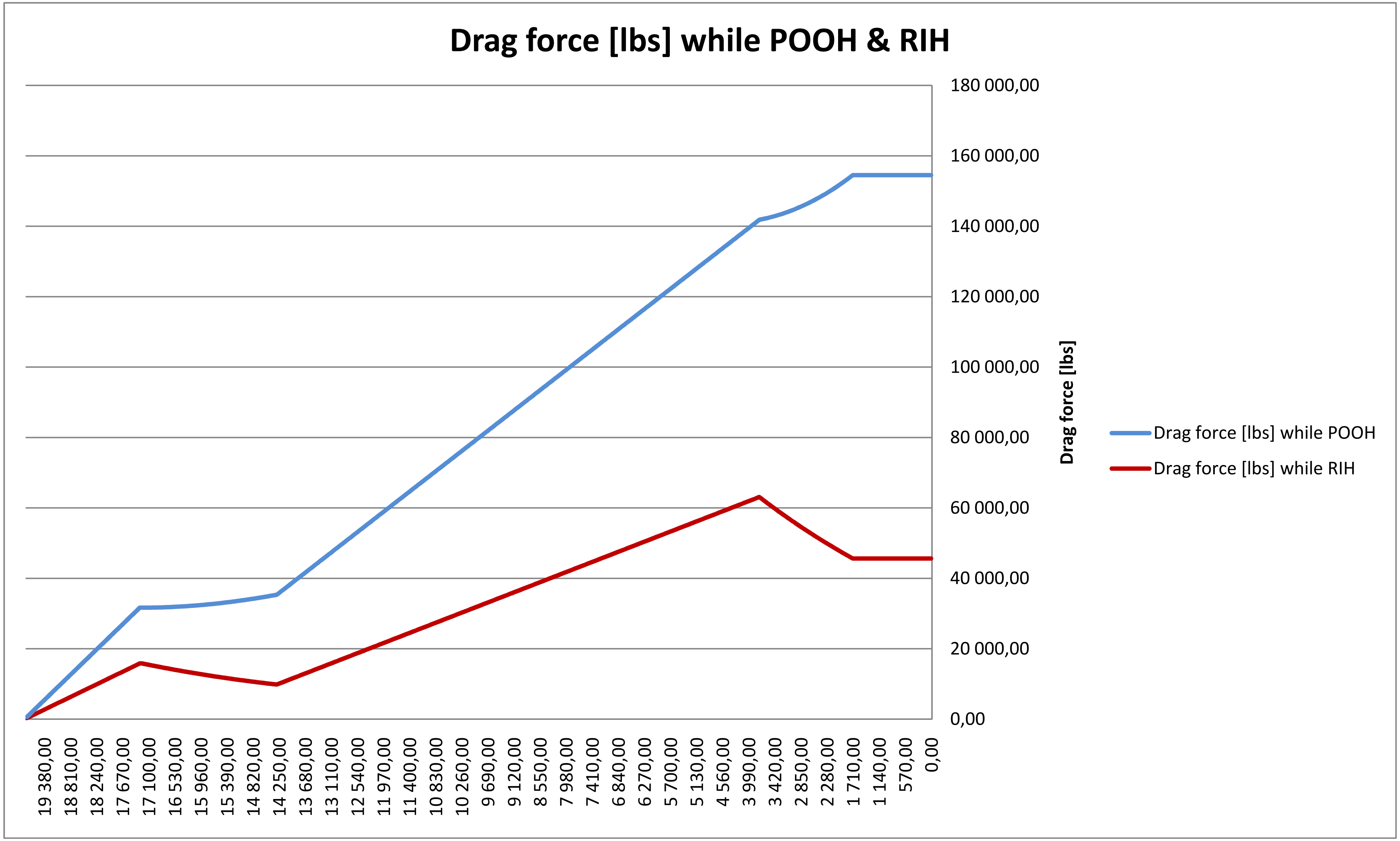


Fig. 36. Drag force comparison of POOH & RIH for the conceptual well

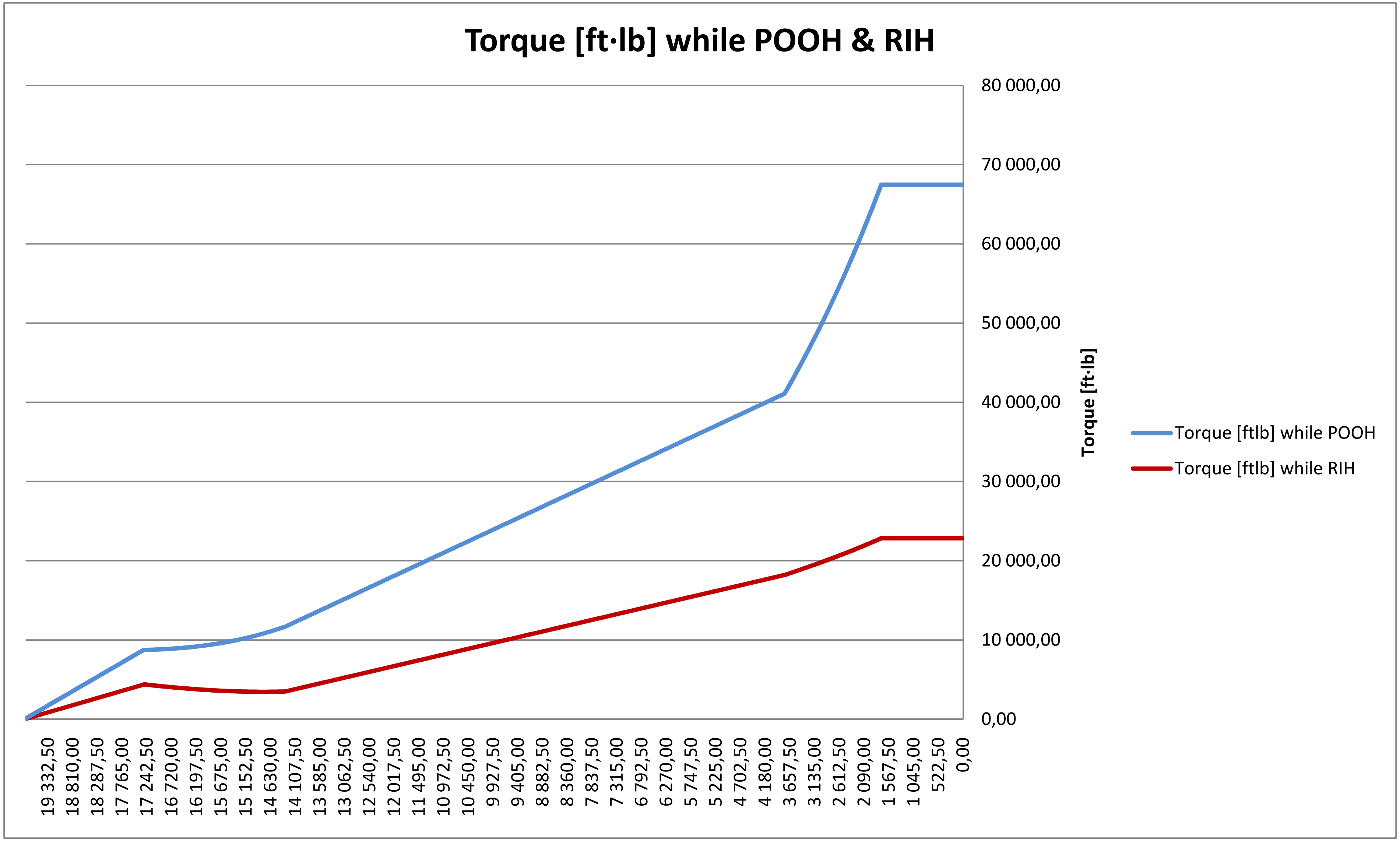


Fig. 37. Torque comparison of POOH & RIH for the conceptual well

6.2.1 Conclusion

- after analysis values (results) got from the model seem to be absolutely reasonable
- the is a possibility of minimizing hook load, drag forces, torque values (will be shown in next chapters)
- shapes of the graphs confirm reasonable values and realistic well concept

6.3 String weight

6.3.1 Introduction to results and observations

Three different materials of pipe with different dimensions have been presented, as following:

<u>steel S-135</u>

- 4 ½"
- 5"
- 5 ½"

<u>aluminum 2014-T6</u>

- 4 ½"
- 5"
- 5 ½"

<u>composite (e-glass/graphite/epoxy)</u>

- 3 3/8"
- 5 ½"

String weight has the largest impact on calculated values (hook load, drag force, torque).

Results from the calculations are presented on next pages:

POOH:

	1	2	3	4	5	6	7	8
	S-135, 4 1/2"	**S-135 5"**	**S-135 5 1/2"**	**2014-T6, 4 1/2"**	**2014-T6, 5"**	**2014-T6, 5 1/2"**	**Composite, 3 3/8"**	**Composite, 5 1/2"**
Unit pipe weight	23,06	28,28	28,85	11,3	13,7	14,6	3,067	12,5
Tool joint radius	0,276	0,276	0,312	0,255	0,292	0,307	0,141	0,292
Hook load	343 818,97	421 647,89	430 146,45	168 480,24	204 263,65	217 682,43	45 728,22	186 371,95
Drag force	111 099,01	136 248,04	138 994,20	54 410,40	66 004,18	70 340,22	14 776,26	60 222,79
Torque value	45 542,00	55 851,16	64 408,63	20 618,75	28 625,11	32 072,65	3 094,40	26 117,80

Tab. 19. Comparison of results for different pipes' materials while POOH

RIH:

	1	2	3	4	5	6	7	8
	S-135, 4 1/2"	**S-135 5"**	**S-135 5 1/2"**	**2014-T6, 4 1/2"**	**2014-T6, 5"**	**2014-T6, 5 1/2"**	**Composite, 3 3/8"**	**Composite, 5 1/2"**
Unit pipe weight	23,06	28,28	28,85	11,3	13,7	14,6	3,067	12,5
Tool joint radius	0,276	0,276	0,312	0,255	0,292	0,307	0,141	0,292
Hook load	95 300,95	116 873,85	119 229,51	46 699,95	56 618,52	60 337,98	12 675,11	51 659,23
Drag force	64 385,31	78 959,96	80 551,44	31 550,48	38 251,47	40 764,34	8 563,30	34 900,97
Torque value	23 305,76	28 581,39	32 960,61	10 551,48	14 648,67	16 412,93	1 583,54	13 365,58

Tab. 20. Comparison of results for different pipes' materials while RIH

Moreover, visual comparison of hook load, drag force and torque is presented below:

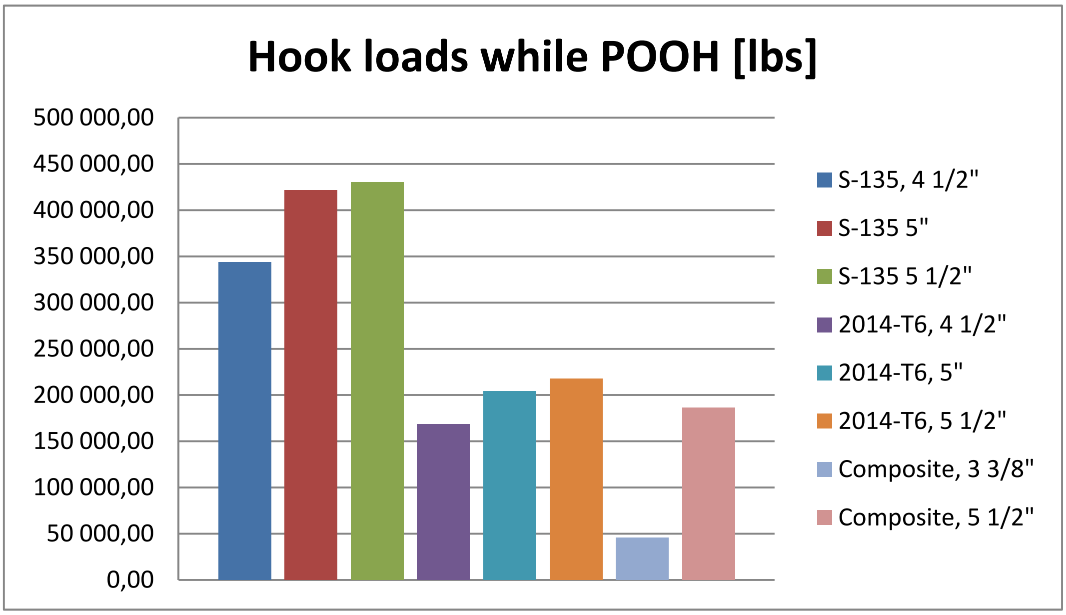


Fig. 38. Hook loads while POOH for different pipes

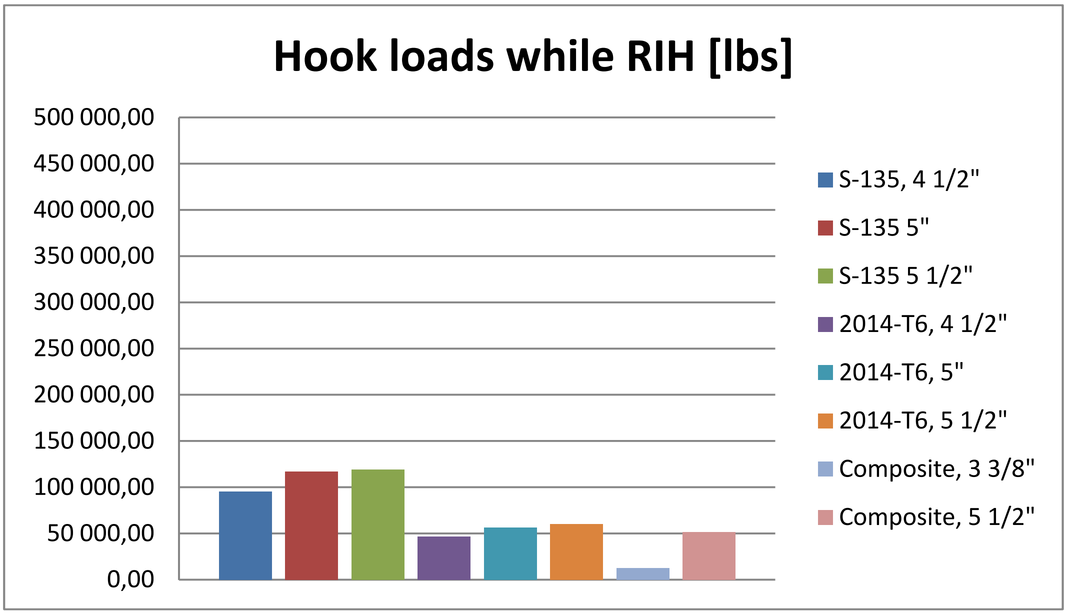


Fig. 39. Hook loads while RIH for different pipes

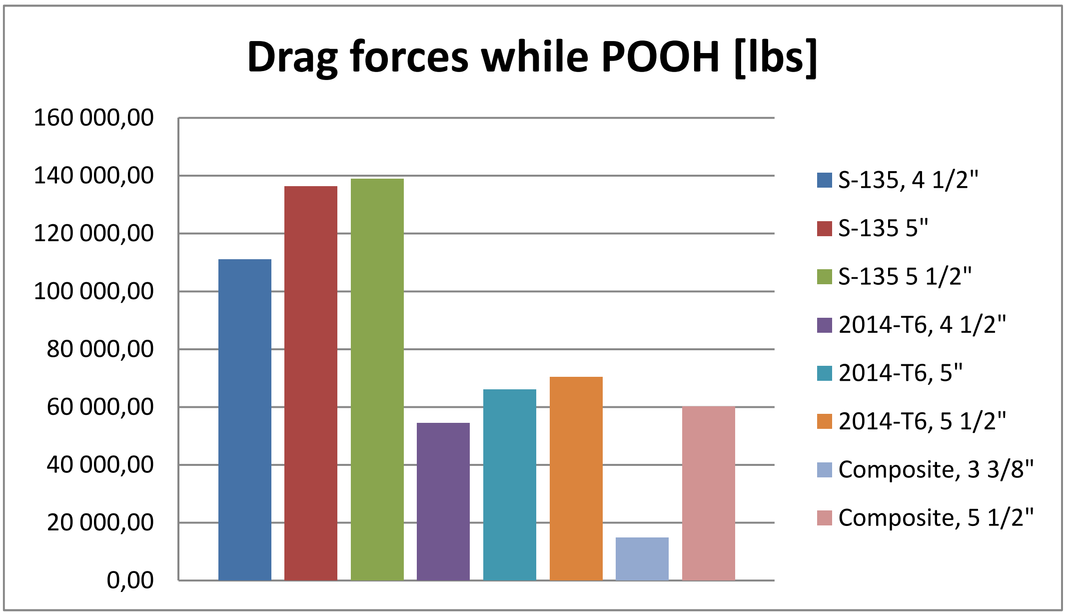


Fig. 40. Drag forces while POOH for different pipes

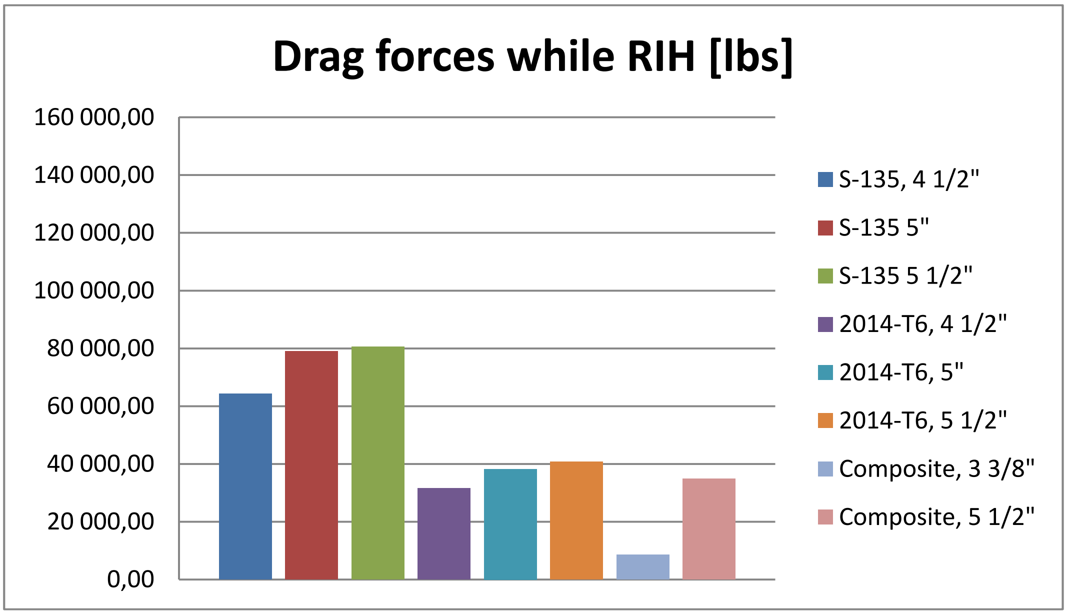


Fig. 41. Drag forces while RIH for different pipes

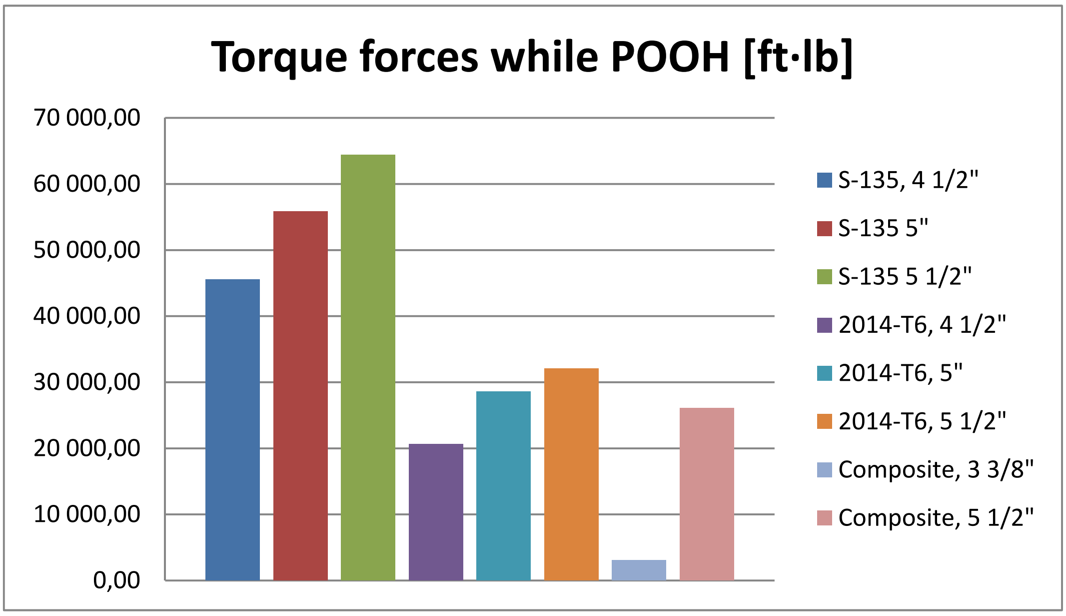


Fig. 42. Torque forces while POOH for different pipes

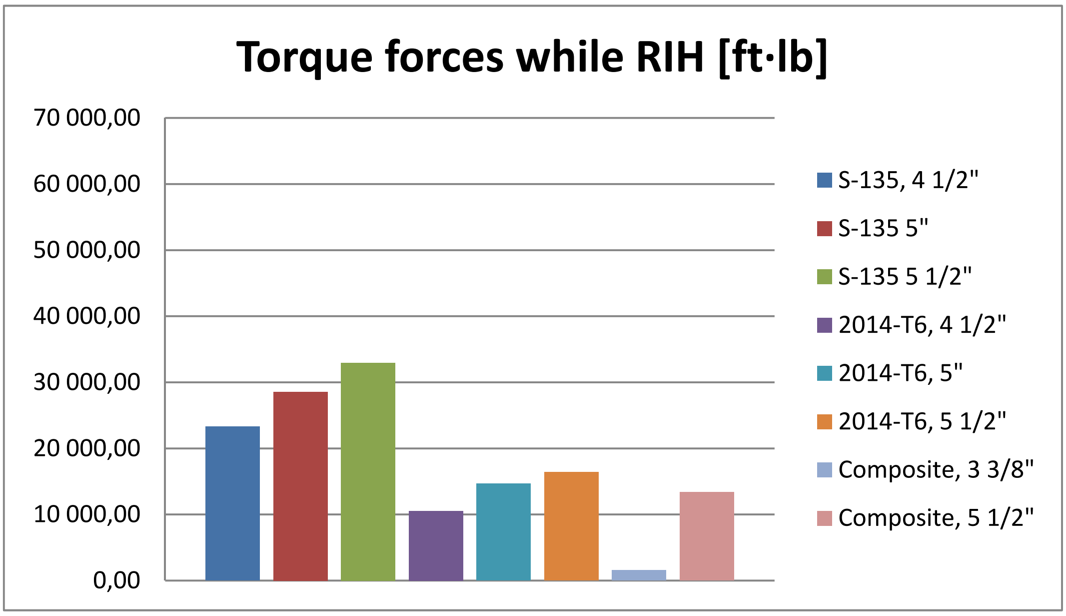


Fig. 43. Torque forces while RIH for different pipes

6.3.2 Conclusion

- the heaviest pipes are made of steel (S-135) and they cause the largest load on the hook
- aluminum and composite pipes (excluding 3 $^{3/8}$") cause twice less load on the hook
- relationship between material and size is represented by constant trend for different materials (the larger OD of a pipe, the larger values such as hook load, drag force, torque)
- the best pipe in the breakdown: Aluminum 2014-T6 4 ½" drill pipe (represents the smallest drag force and torque (excluding 3 $^{3/8}$") as well as hook load)

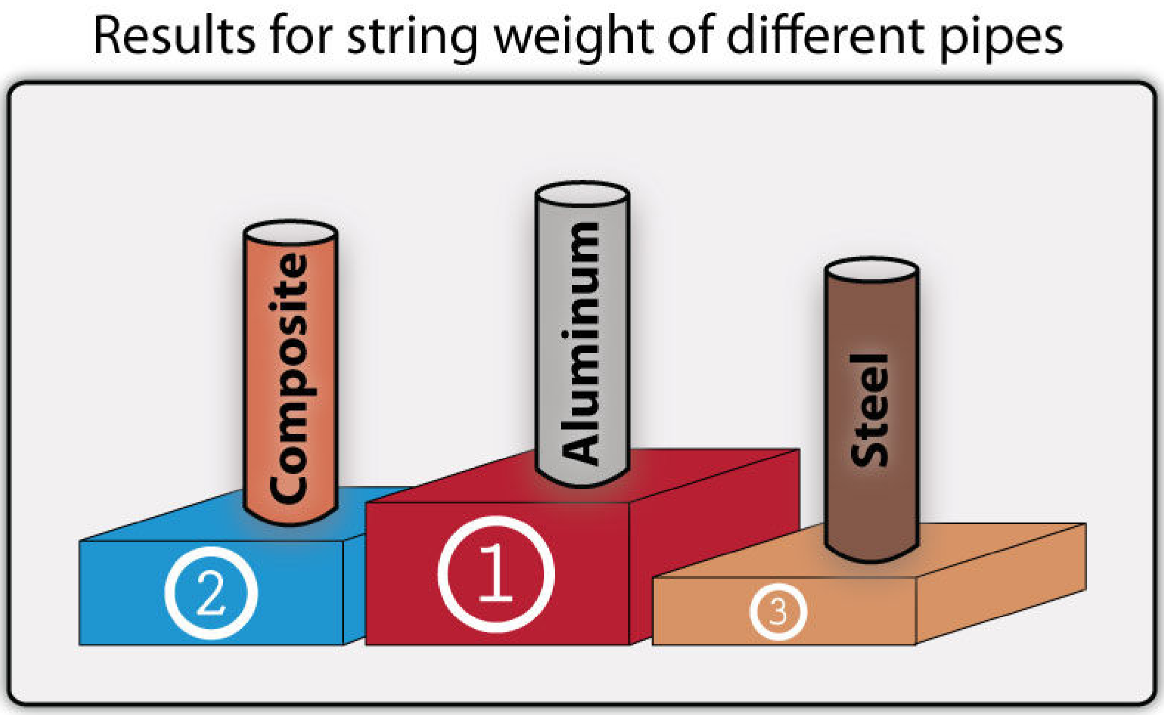


Fig. 44. Results for string weight of different pipes

6.4 Buckling evaluation

6.4.1 Introduction to results and observations

Three different materials with different pipe sizes have been considered:

steel S-135

- 4 ½”
- 5”
- 5 ½”

aluminum 2014-T6

- 4 ½”
- 5”
- 5 ½”

composite (e-glass/graphite/epoxy)

- 3 $^{3/8}$”
- 5 ½”

Except pipe properties, some material properties had to be considered as well, especially:

- Young’s modulus
- material density

Other variables that have been defined are:

- normal force (one acting on a bit)
- ‘K’ factor (to classify buckling as sinusoidal one)
- inclination (the maximal inclination obtained in the model well pattern)

Results obtained from mentioned-above data can be seen on next pages:

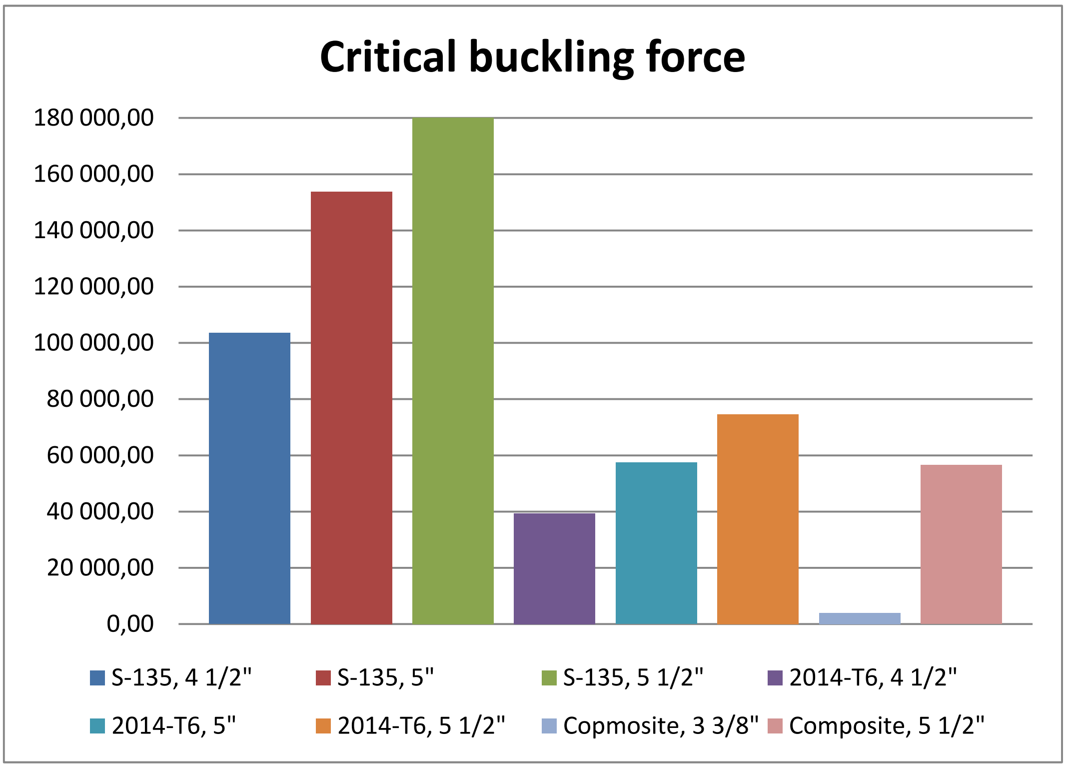


Fig. 45. Critical buckling force for different pipes

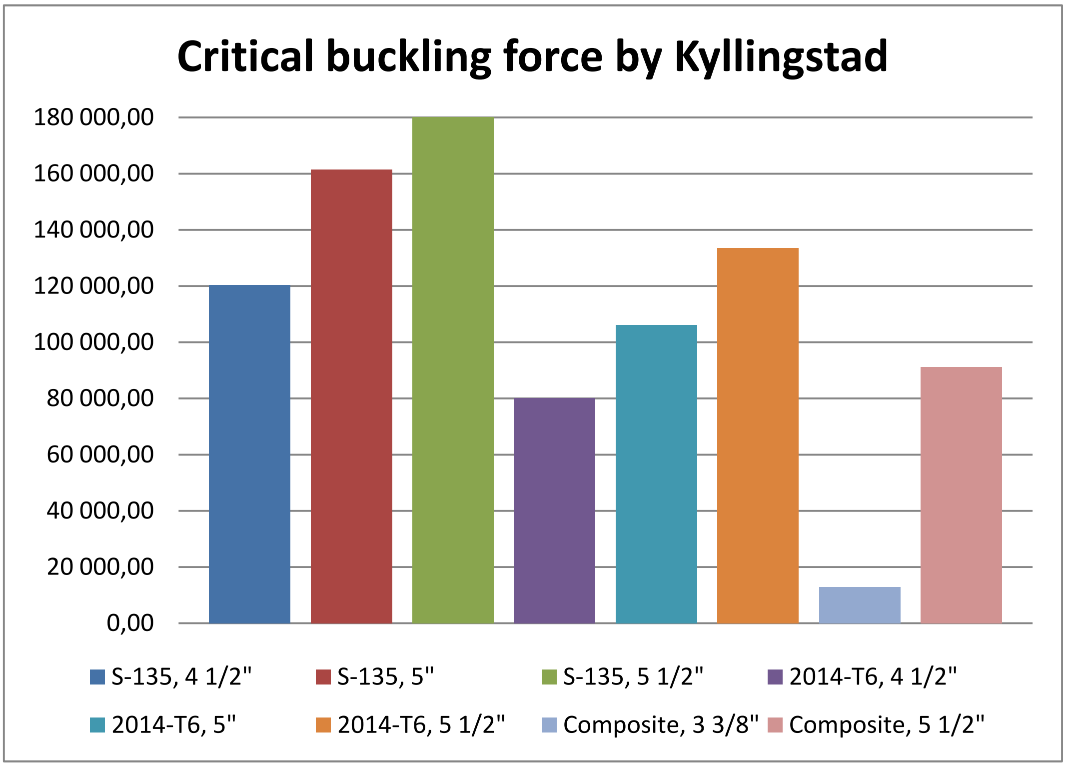


Fig. 46. Critical buckling force by Kyllingstad for different pipes

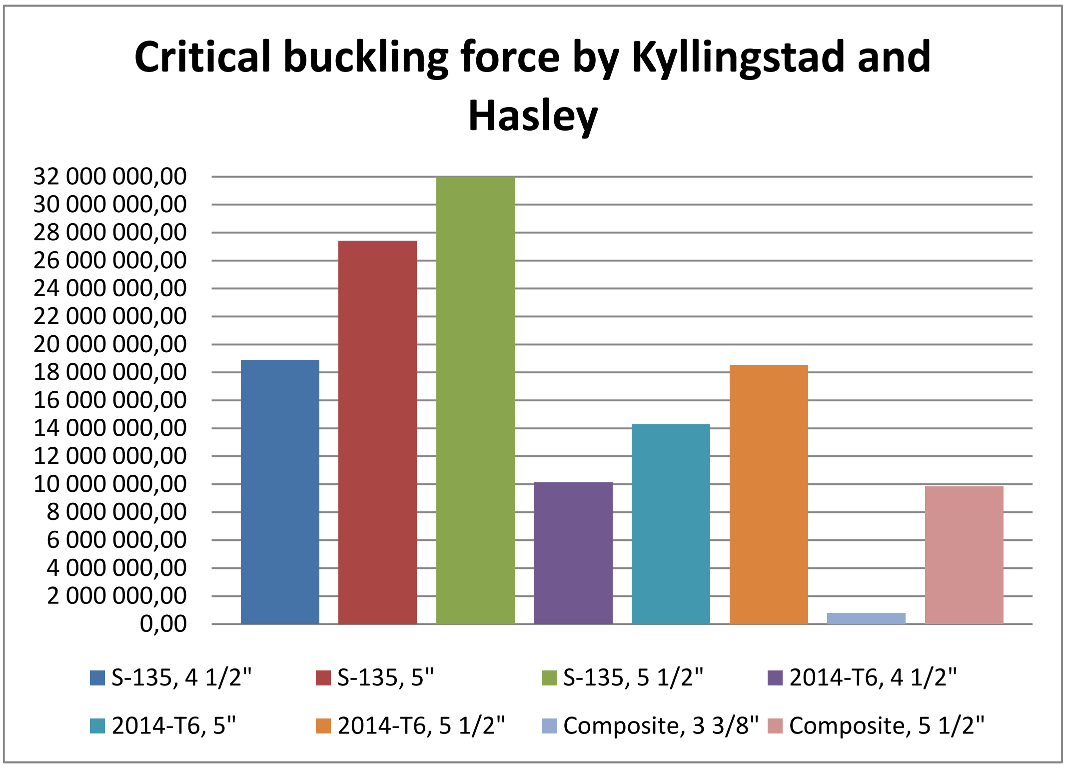


Fig. 47. Critical buckling force by Kyllingstad and Hasley for different pipes

Critical buckling force in this case is the maximal axial force affecting the pipe in a way that it will buckle when the force is exceeded.

6.4.2 Conclusion

- the greatest resistance to buckling phenomenon have steel pipes
- the lowest resistance to buckling phenomenon have composite pipes
- buckling is strongly dependant on a relationship between pipe size (Outside Diameter) and hole size, which is defined as radial clearance
- the trend for different materials and sizes is the same for different buckling models, what indicates that test had been carried out in a proper way

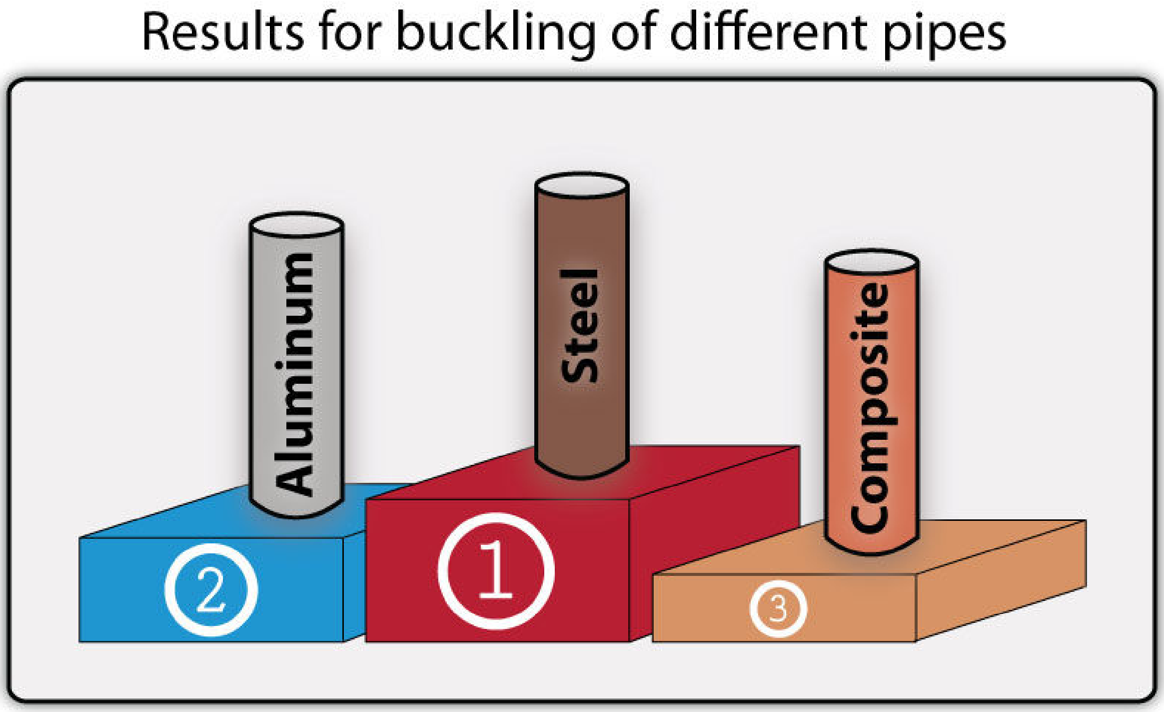


Fig. 48. Results for buckling of different pipes

6.5 Directional profile

6.5.1 Introduction to results and observations

Three different directional profiles have been considered:

- model profile
- optimized model profile I (Kick-Off-Point 200 meters deeper)
- optimized model profile II (DLS set up to 1,00°/100ft)

Optimized model profiles have 6 sections, which means, 1 more than the model one.

Results obtained from mentioned well patterns for hook load, drag force and torque are presented below.

POOH:

	Model pattern	KOP +200	DLS +1
Hook load	336 960,48	326 122,78	312 487,23
Drag force	108 882,81	107 364,29	85 106,06
Torque	44 633,53	43 003,13	37 007,55

Tab. 21. Results of calculated variables obtained from different well patterns while POOH

RIH:

	Model pattern	KOP +200	DLS +1
Hook load	93 399,89	91 358,88	119 395,91
Drag force	63 100,96	62 856,50	40 112,46
Torque	22 840,85	21 421,08	16 096,31

Tab. 22. Results of calculated variables obtained from different well patterns while RIH

Visual interpretations are shown on next pages as well:

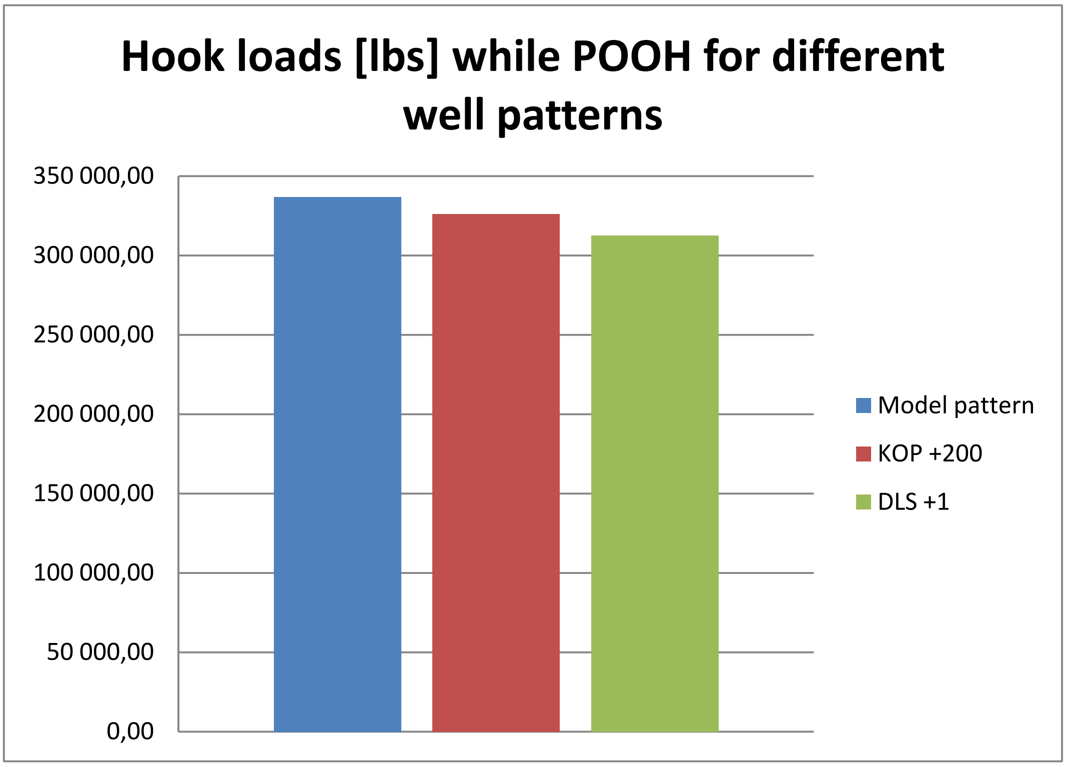


Fig. 49. Hook loads while POOH for different well patterns

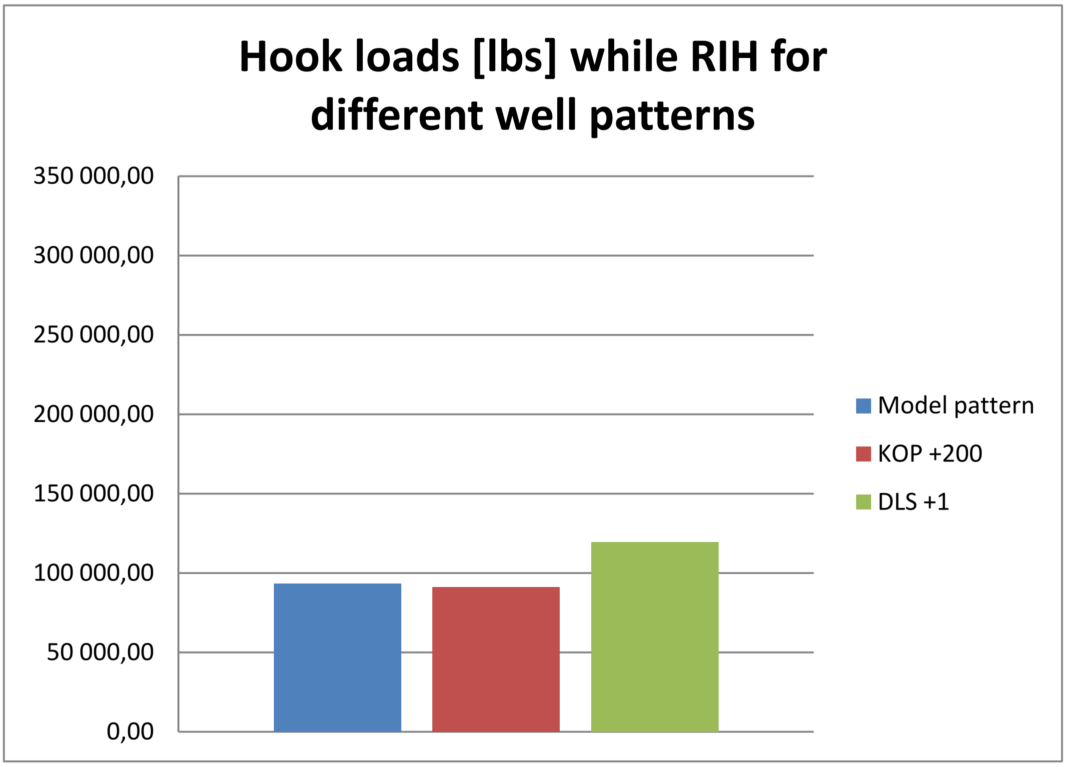


Fig. 50. Hook loads while RIH for different well patterns

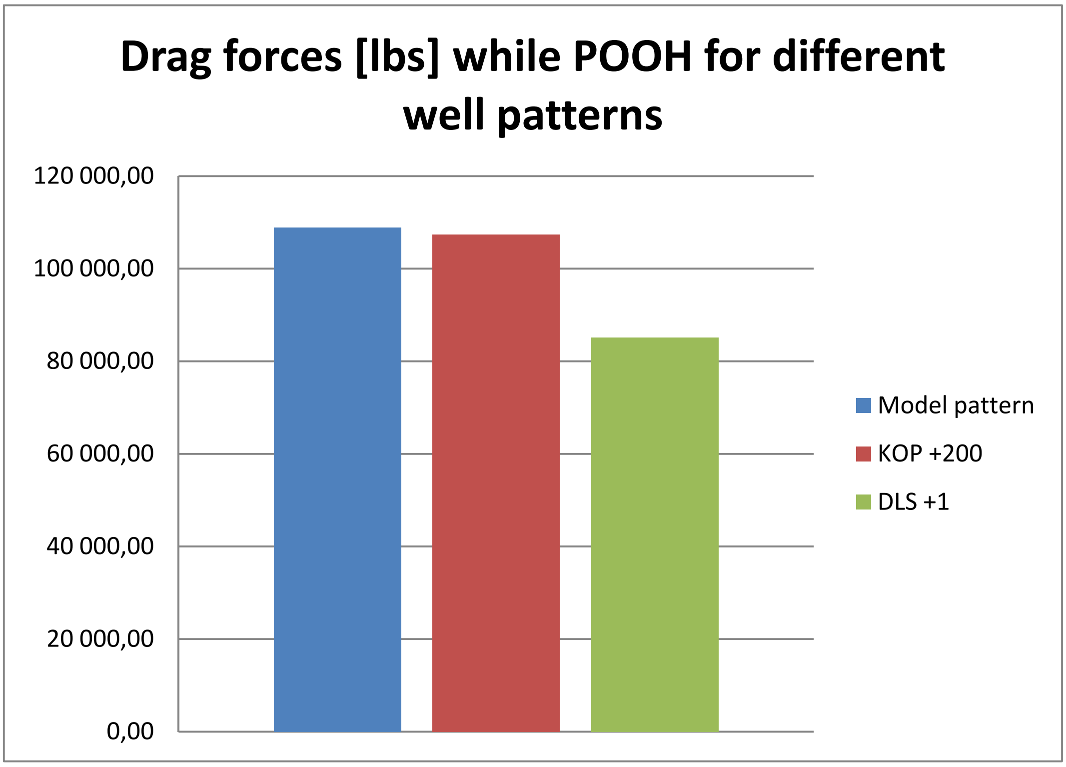


Fig. 51. Drag forces while POOH for different well patterns

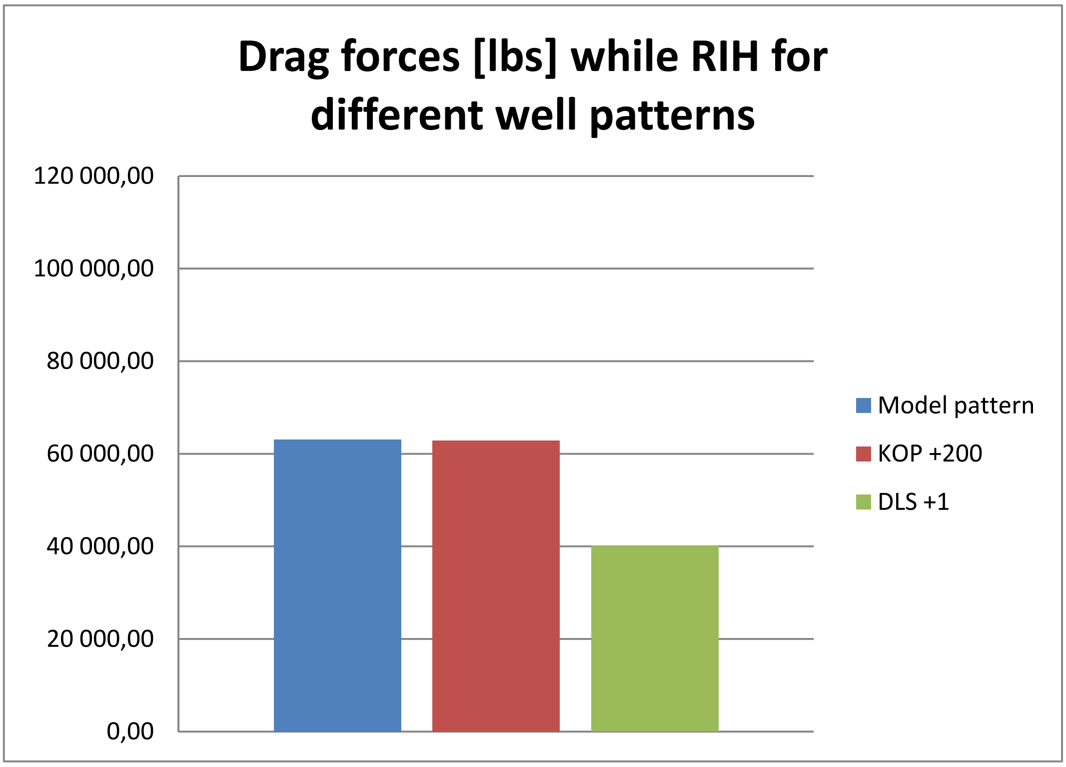


Fig. 52. Drag forces while RIH for different well patterns

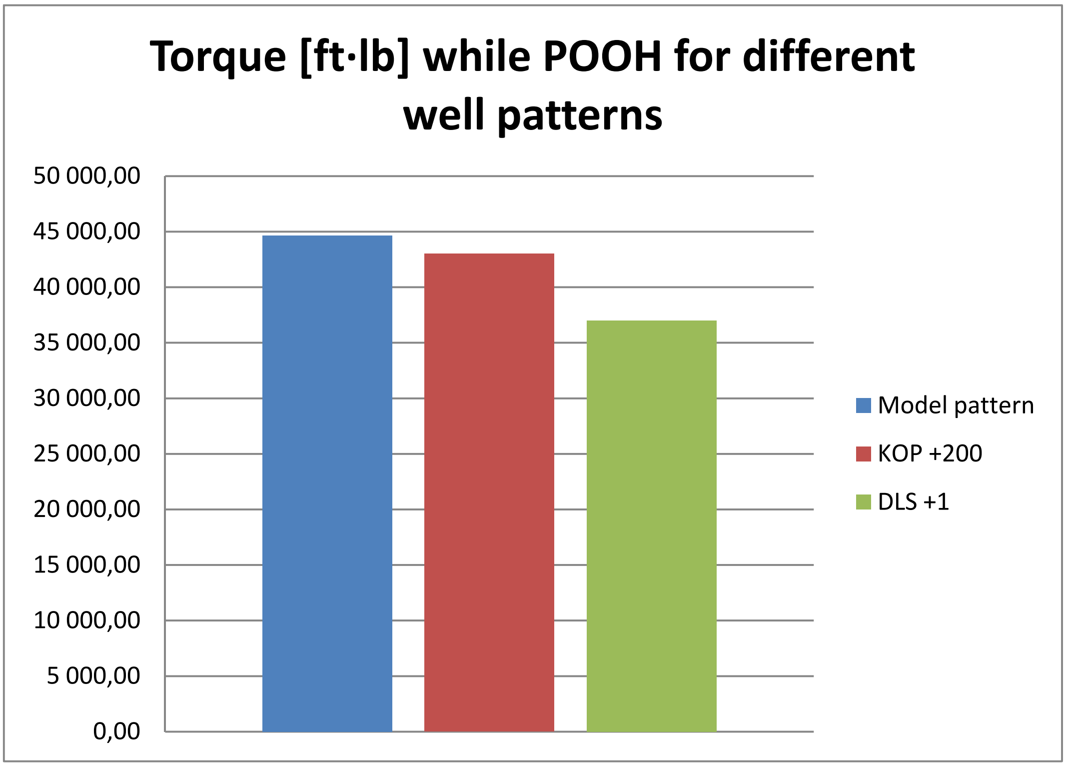


Fig. 53. Torque while POOH for different well patterns

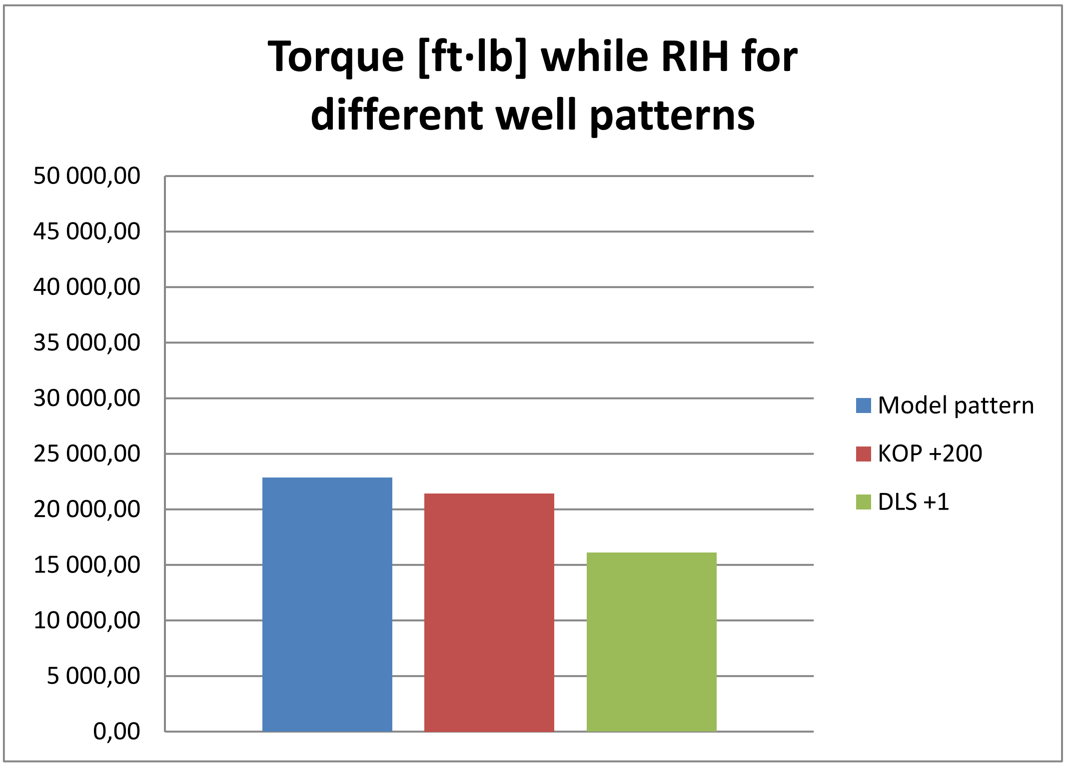


Fig. 54. Torque while RIH for different well patterns

6.5.2 Conclusion

- values obtained from additional profiles are lower than from original one
- optimal well determined by Schlumberger's software – 'Petrel' DID NOT offer the lowest values for examined values (presumably no drilling package installed)
- building at lower rates will yield the least amount of drag
- conversely, building at higher rates will yield the greatest amount of drag
- directional profile makes relatively small difference when it refers to hook load, drag force and torque

6.6 Friction coefficient

6.1.1 Introduction to results and observations

In the chapter for different drilling muds have been considered:

- OBM (Oil Based Mud) with friction factors: 0,18 (cased hole)/0,21 (open hole)

- WBM (Water Based Mud) with friction factors: 0,30 (cased hole)/0,33 (open hole)

- Brine with friction factors: 0,35 (cased hole)/0,35 (open hole)

- Air & Mist with friction factors: 0,45 (cased hole)/0,45 (open hole)

Calculations have been performed both for tripping out and tripping in operations.

Results are shown below.

POOH:

	OBM	WBM	Brine	A&M
Values	0,18/021	0,30/0,33	0,35/0,35	0,45/0,45
Hook load [lbs]	260 098,02	336 960,48	372 041,59	463 409,95
Drag force [lbs]	55 098,88	108 882,81	133 390,60	201 576,93
Torque [ft·lb]	23 339,57	44 633,53	54 353,44	79 627,97

Tab. 23. Results of calculated variables for different mud types while POOH

RIH:

	OBM	WBM	Brine	A&M
Values	0,18/0,21	0,30/0,33	0,35/0,35	0,45/0,45
Hook load [lbs]	119 746,21	93 399,89	84 840,11	69 103,74
Drag force [lbs]	39 530,89	63 100,96	71 778,18	90 468,53
Torque [ft·lb]	15 560,72	22 840,85	25 203,90	29 502,22

Tab. 24. Results of calculated variables for different mud types while RIH

Visual representation is presented on next pages.

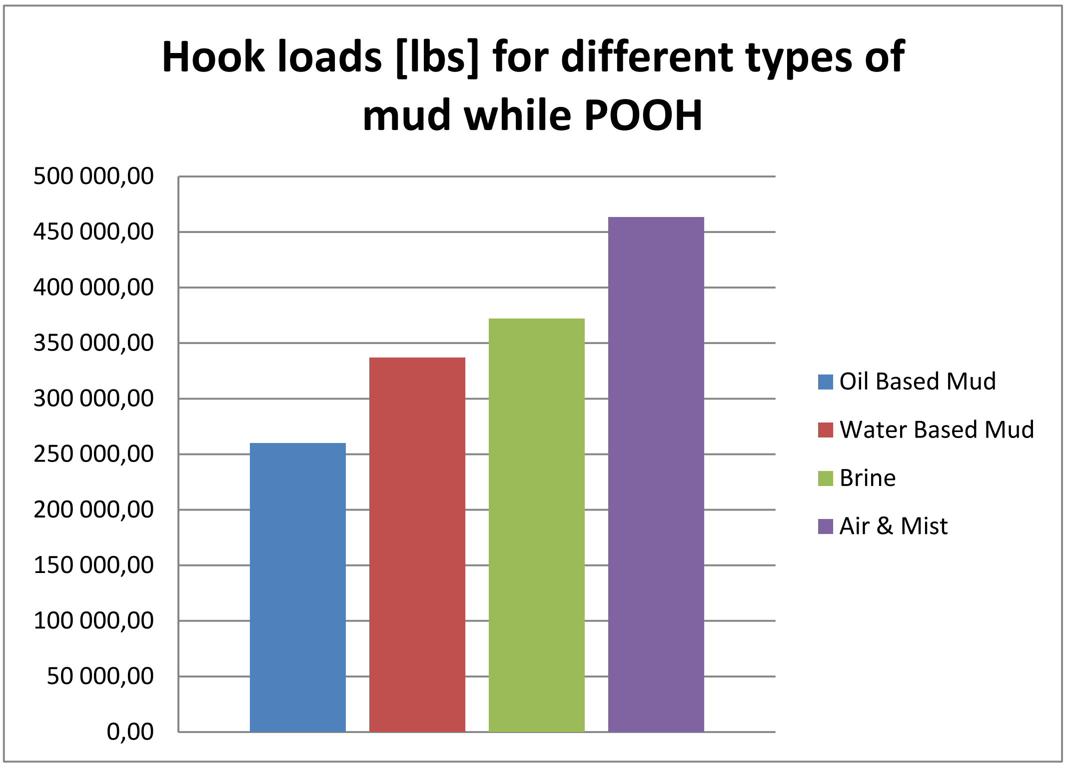


Fig. 55. Hook loads for different types of mud while POOH

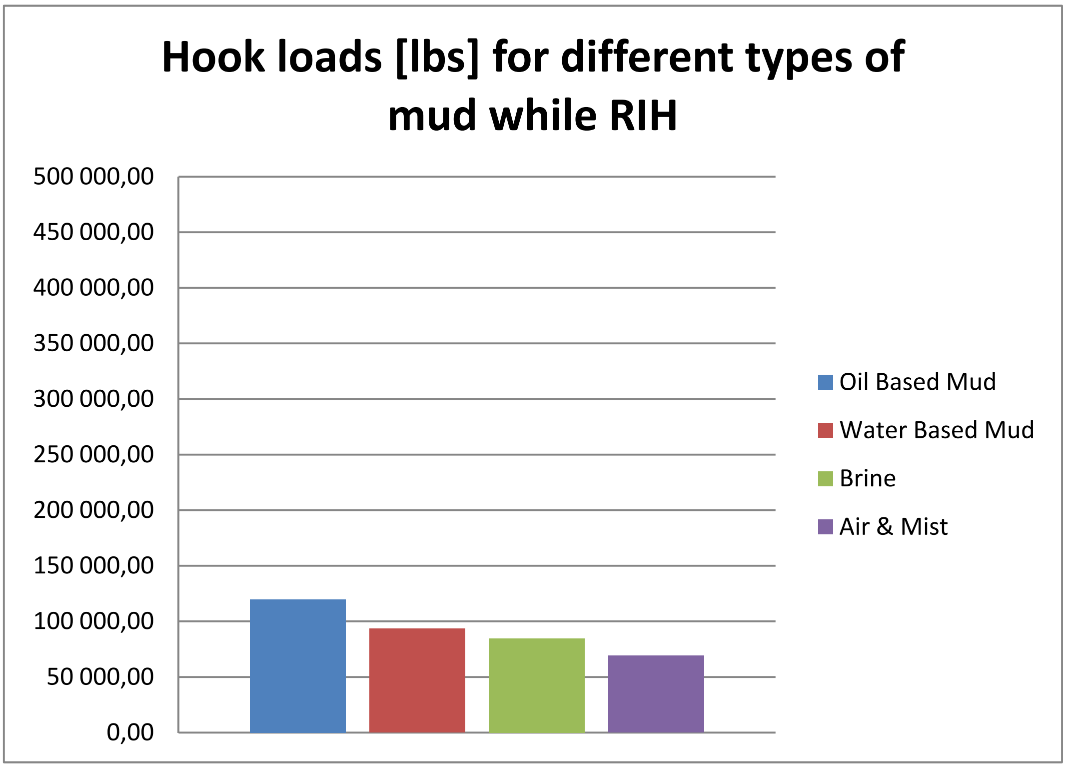


Fig. 56. Hook loads for different types of mud while RIH

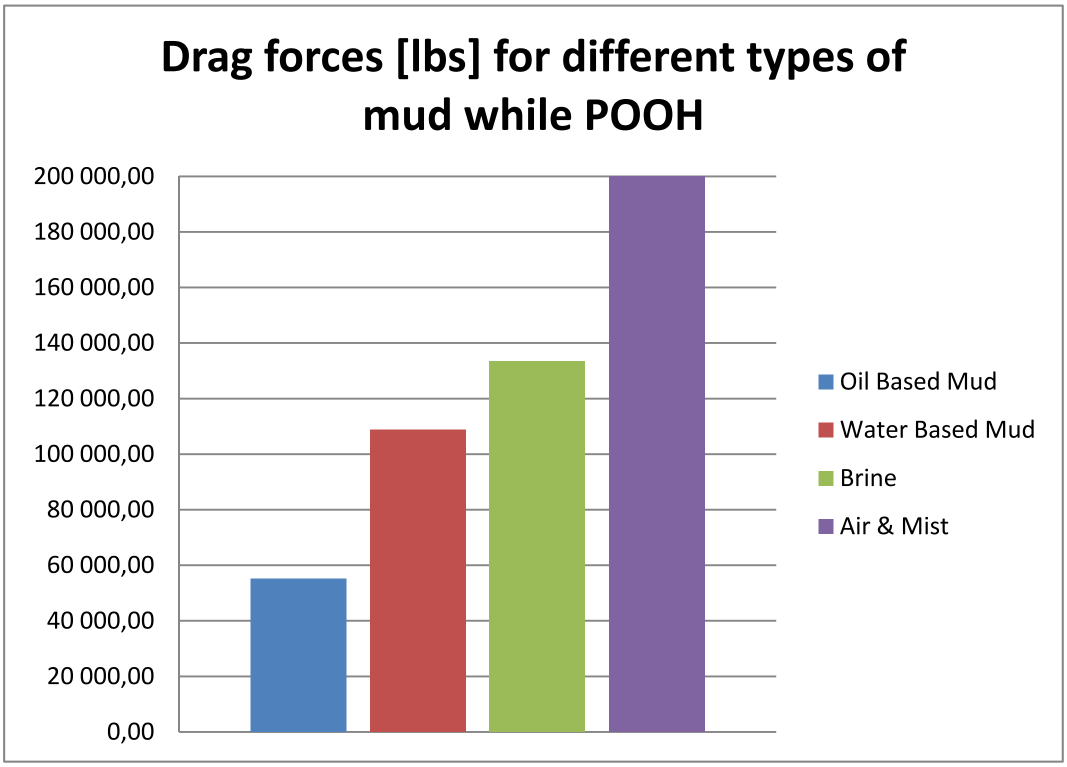


Fig. 57. Drag forces for different types of mud while POOH

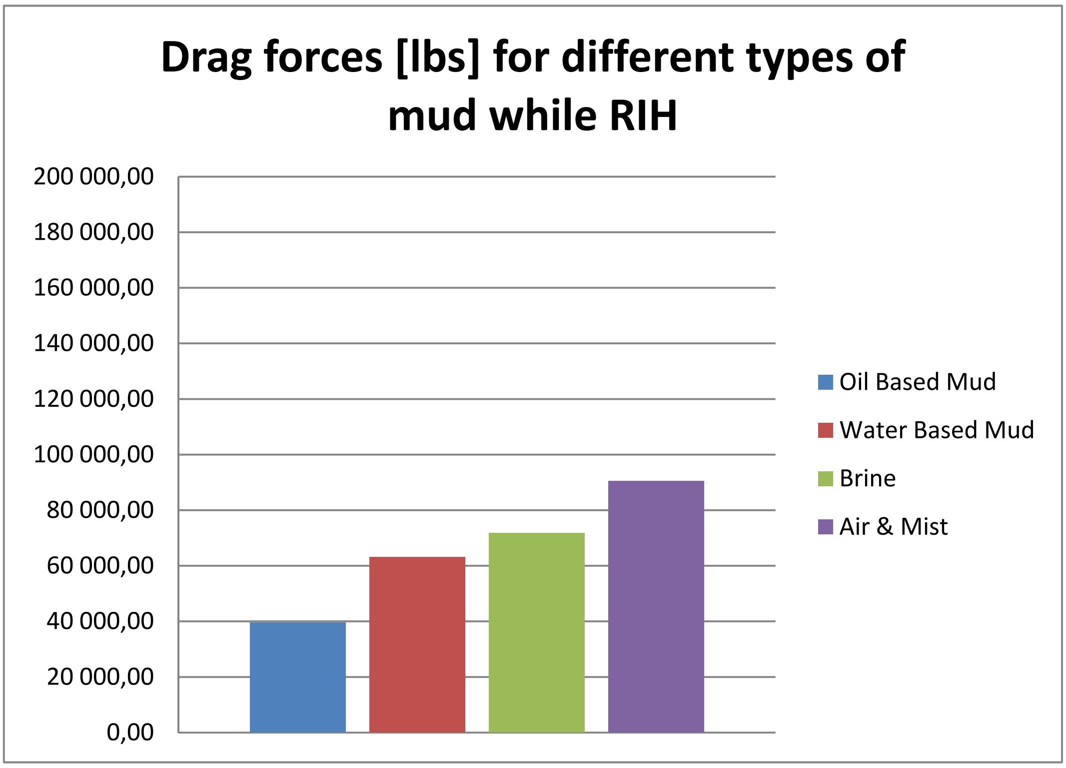


Fig. 58. Drag forces for different types of mud while RIH

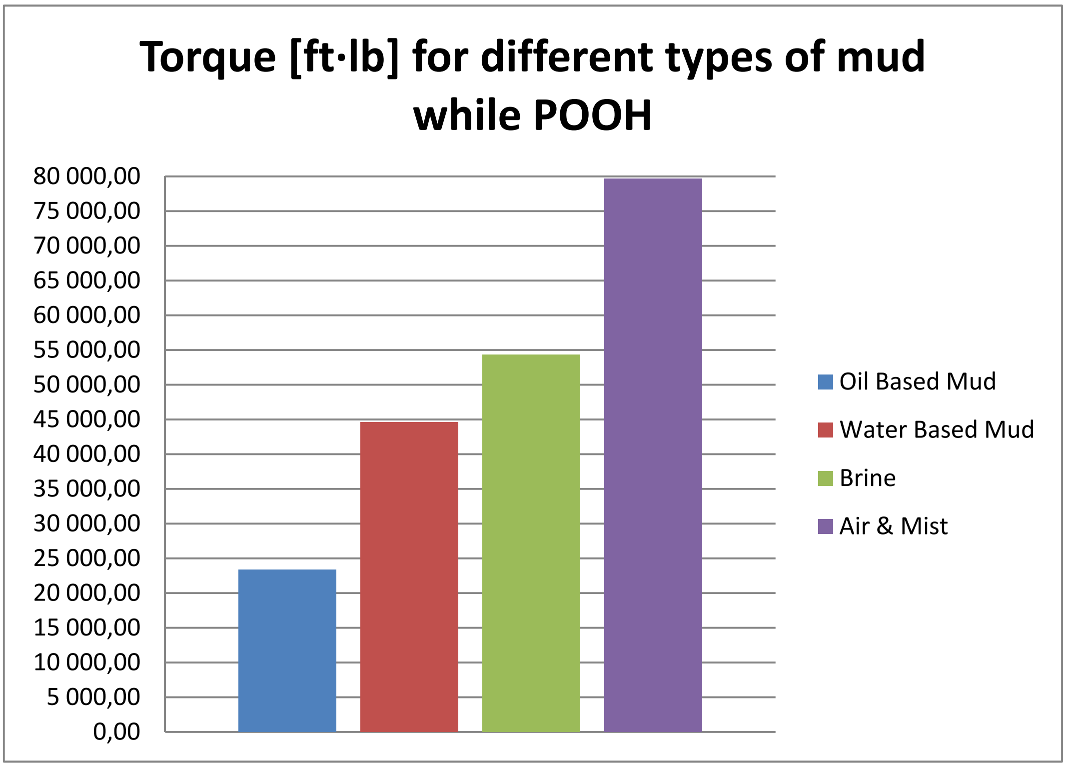


Fig. 59. Torque for different types of mud while POOH

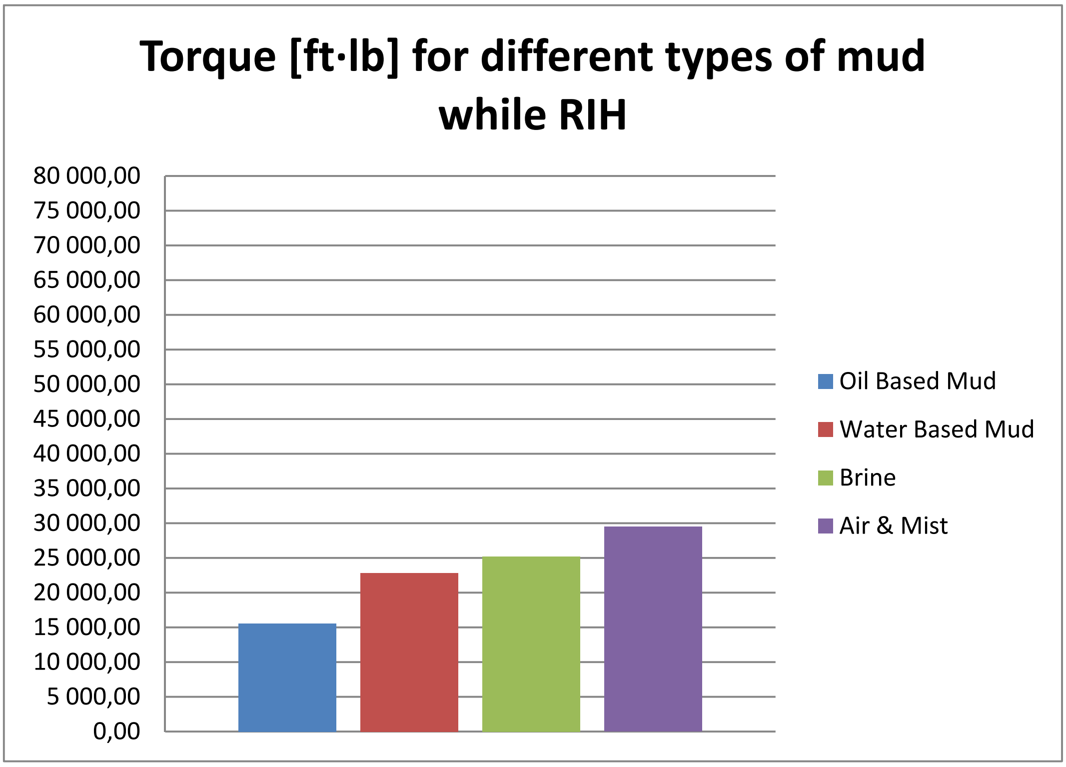


Fig. 60. Torque for different types of mud while RIH

Moreover, differences between light and heavy drilling mud (the one that obtained the best results in the calculations above) are shown below.

POOH (for 10,2 ppg OBM)**:**

		10,2 ppg OBM	
Depth [ft]	**Hook load [lbs]**	**Drag force [lbs]**	**Torque [ft·lb]**
0,00	260 098,02	55 098,88	23 339,57
1 710,00	227 470,18	55 098,88	23 339,57
3 752,50	159 745,66	45 359,72	13 160,69
14 297,50	33 083,79	13 405,86	4 341,43
17 290,00	12 098,41	10 078,52	2 781,67

Tab. 25. Results of variables for 10,2 ppg OBM while POOH

POOH (for 15,2 ppg OBM)**:**

		15,2 ppg OBM	
Depth [ft]	**Hook load [lbs]**	**Drag force [lbs]**	**Torque [ft·lb]**
0,00	236 581,02	50 117,06	21 229,30
1 710,00	206 903,25	50 117,06	21 229,30
3 752,50	145 302,11	41 258,48	11 970,76
14 297,50	30 092,49	12 193,76	3 948,89
17 290,00	11 004,52	9 167,26	2 530,16

Tab. 26. Results of variables for 15,2 ppg OBM while POOH

RIH (for 10,2 ppg OBM)**:**

		10,2 ppg OBM	
Depth [ft]	**Hook load [lbs]**	**Drag force [lbs]**	**Torque [ft·lb]**
0,00	119 746,21	32 543,49	15 560,72
1 710,00	87 118,37	32 543,49	15 560,72
3 752,50	70 302,04	39 530,89	11 416,75
14 297,50	7 547,90	7 577,03	2 597,49
17 290,00	-8 058,63	10 078,52	2 781,67

Tab. 27. Results of variables for 10,2 ppg OBM while RIH

RIH (for 15,2 ppg OBM)**:**

		15,2 ppg OBM	
Depth [ft]	**Hook load [lbs]**	**Drag force [lbs]**	**Torque [ft·lb]**
0,00	108 919,25	29 601,04	14 153,78
1 710,00	79 241,48	29 601,04	14 153,78
3 752,50	63 945,62	35 956,66	10 384,50
14 297,50	6 865,45	6 891,94	2 362,63
17 290,00	-7 330,00	9 167,26	2 530,16

Tab. 28. Results of variables for 15,2 ppg OBM while RIH

Visual representation is shown below.

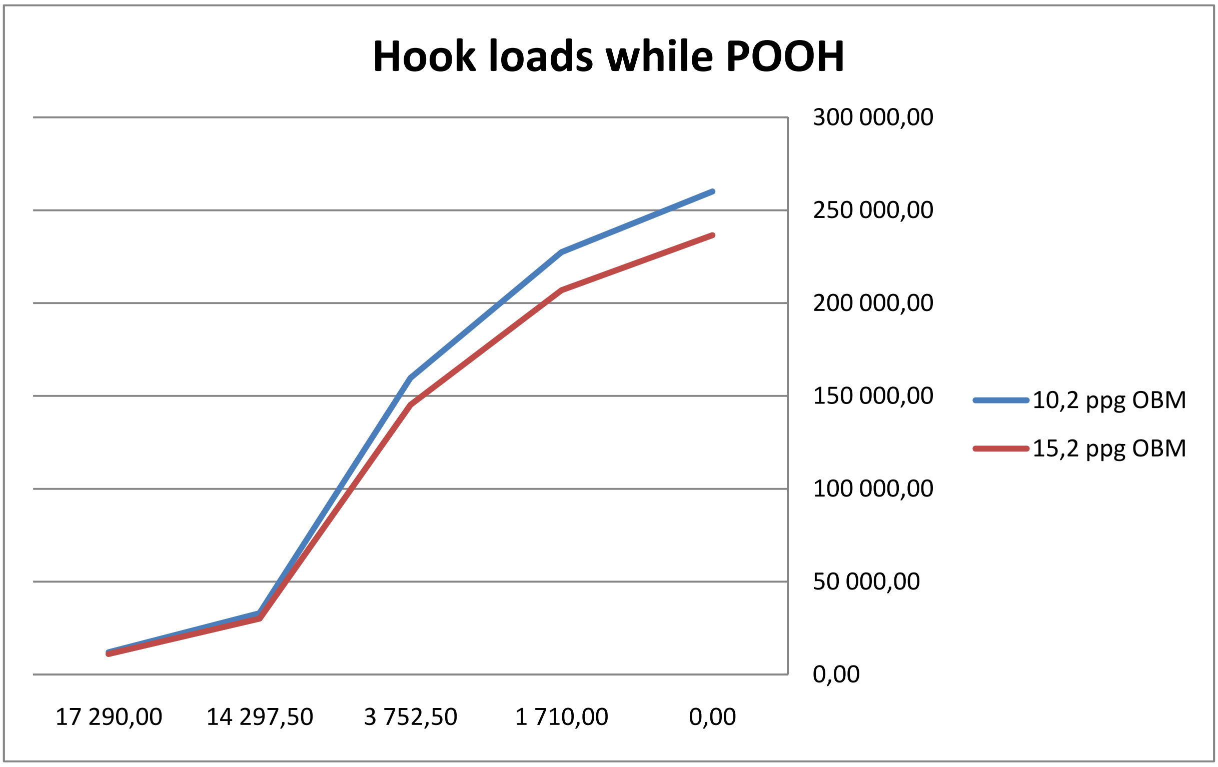


Fig. 61. Hook loads while POOH for different types of mud

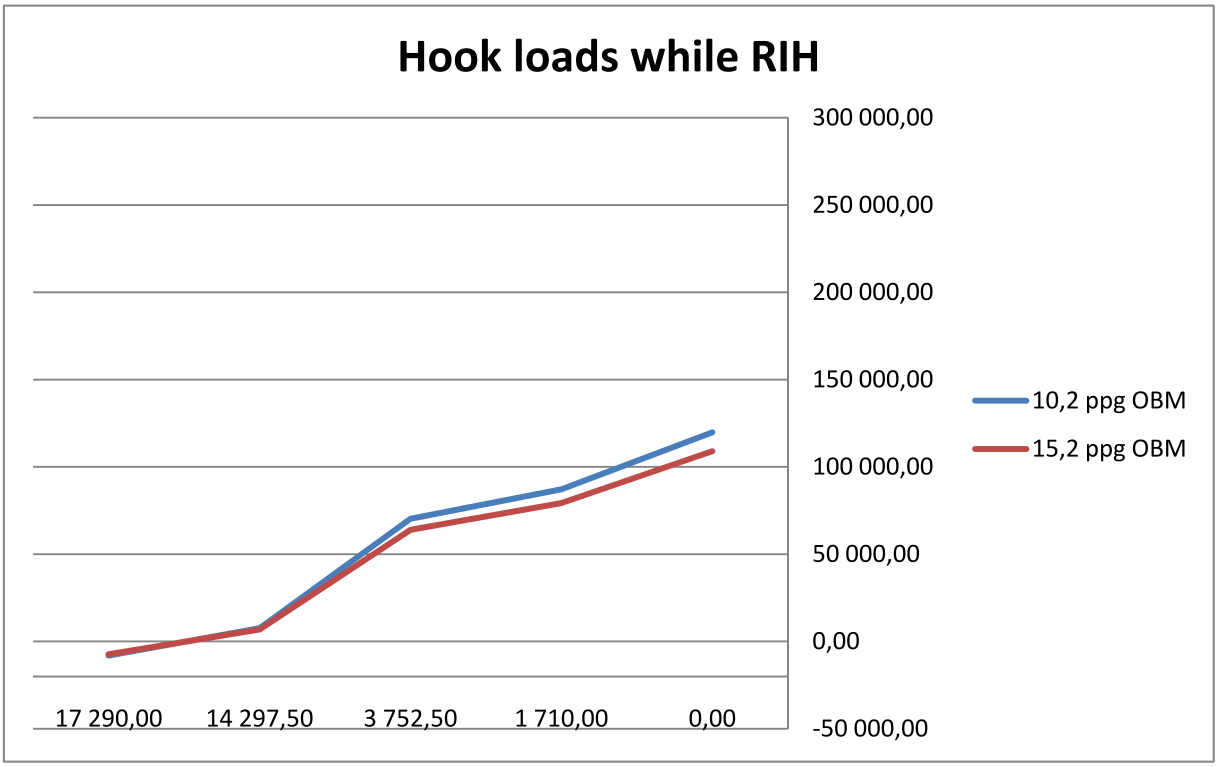


Fig. 62. Hook loads while RIH for different types of mud

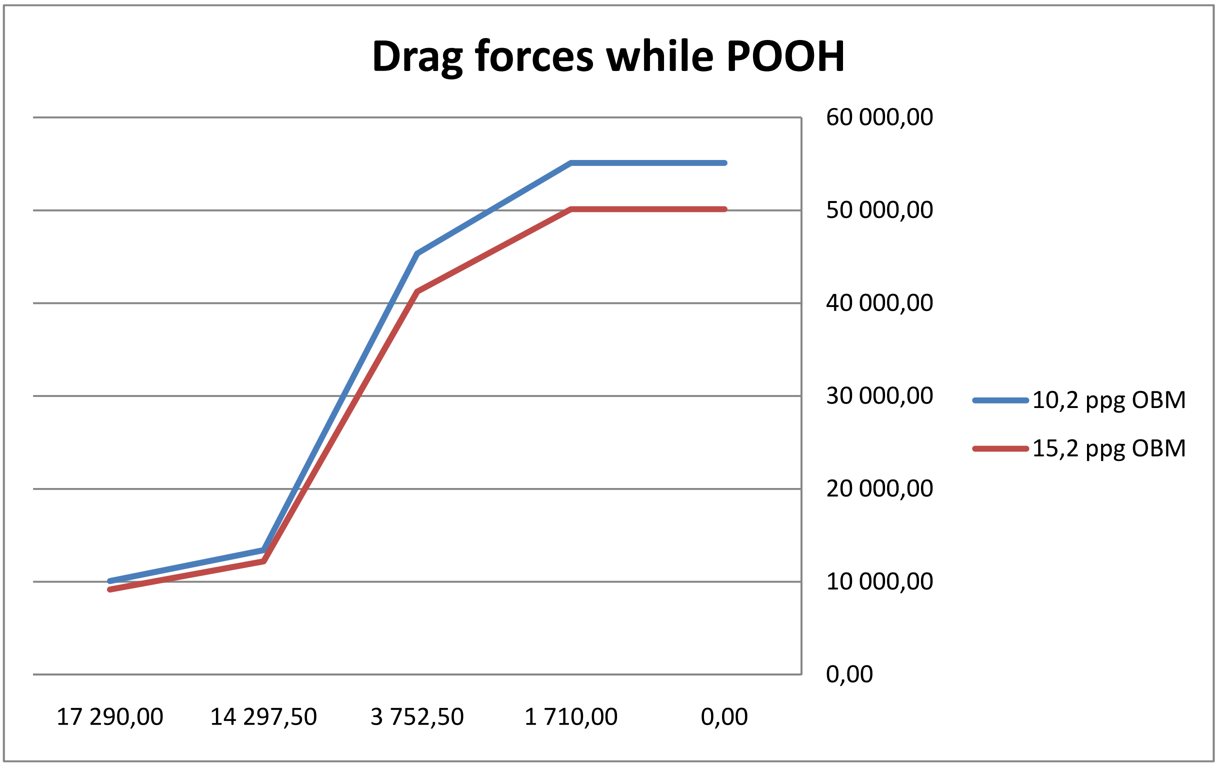


Fig. 63. Drag forces while POOH for different types of mud

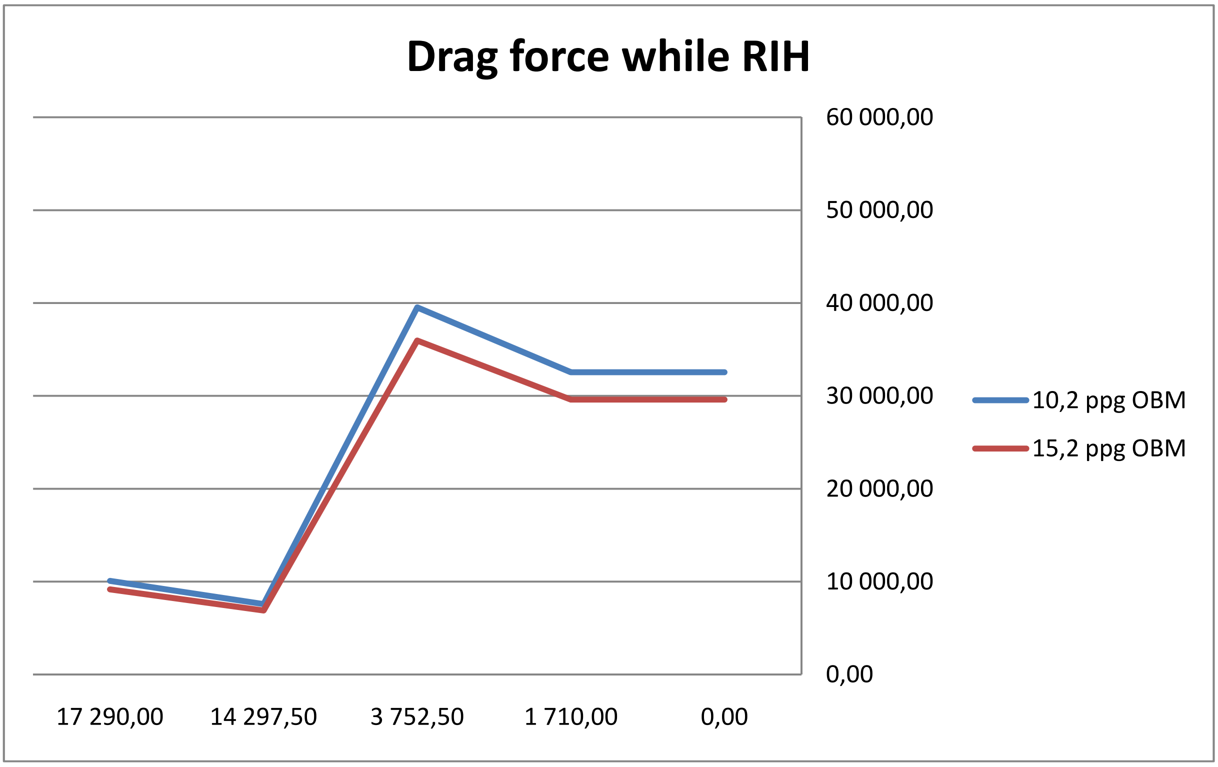


Fig. 64. Drag forces while RIH for different types of mud

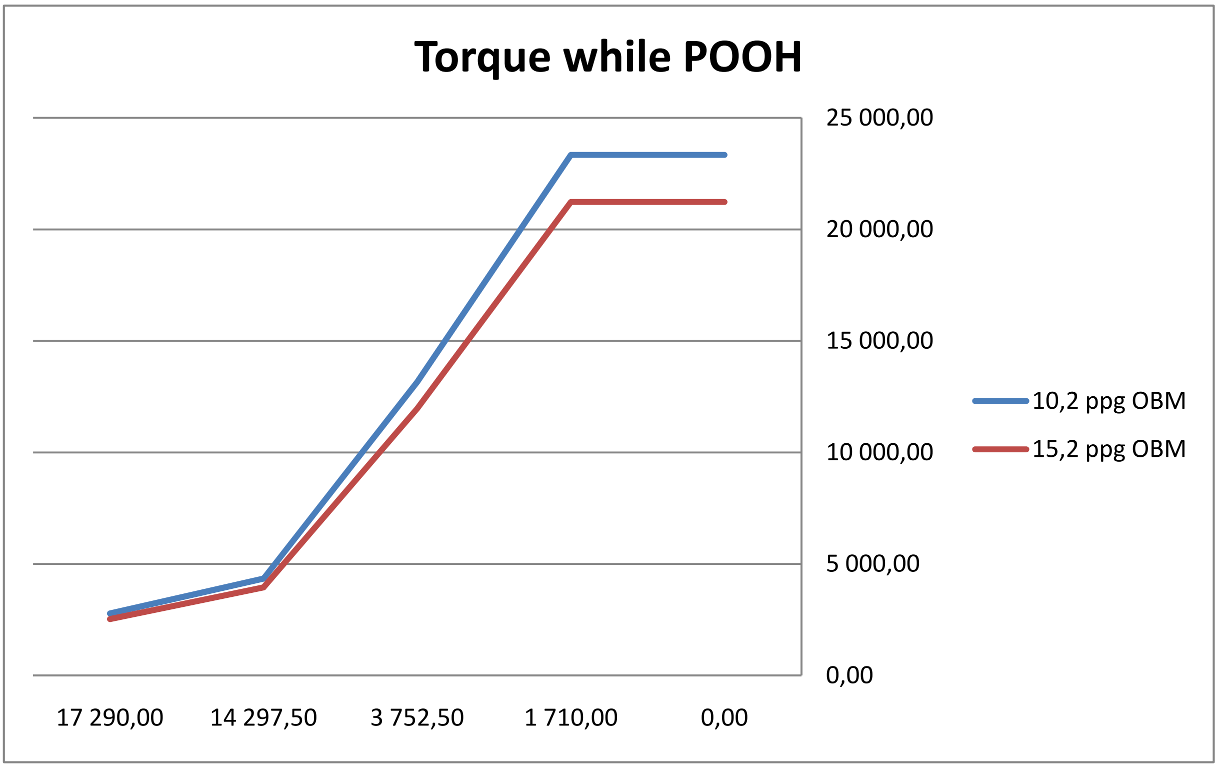


Fig. 65. Torque while POOH for different types of mud

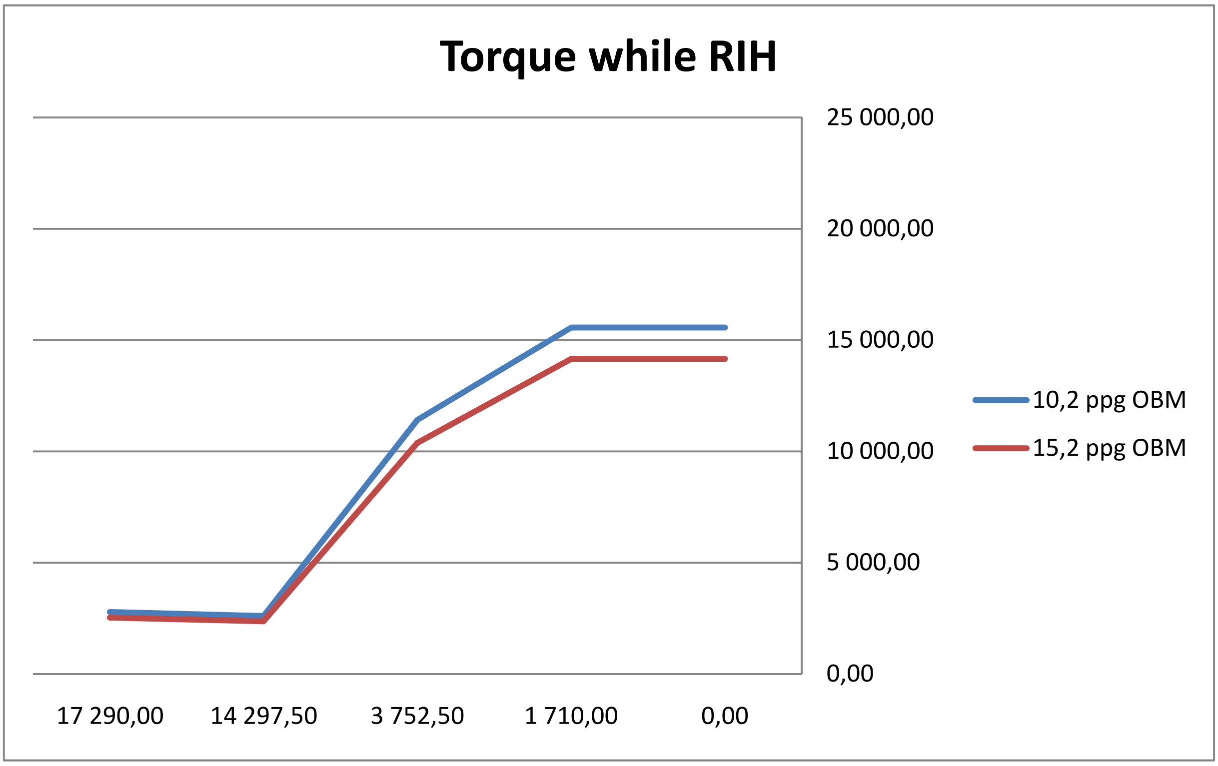


Fig. 66. Torque while RIH for different types of mud

6.6.2 Conclusion

- for Oil Based Mud and Water Based Mud friction coefficients are different for cased- and open hole sections
- for Brine and Air & Mist friction coefficients are the same both for cased- and open hole sections
- Oil Based Mud offers the best conditions while tripping out
- heavy Oil Based Mud offers just little improvement in compare to light one, thus application of it has to be technically and economically justified

6.7 BHA assembly

6.7.1 Introduction to results and observations

Last chapter is to show how chosen type of Bottom Hole Assembly can affect design of the whole string.

Variables from the model well pattern have been utilized, as following:

- Water Based Mud (10,2 ppg) with friction factors: 0,30 (cased hole)/0,33 (open hole)
- drill pipes (22,6 lb/ft)
- length of the string 19.760 ft

Also some additional data has been used, as:

- drill collar 7 x 1 ½" (124,95 ft/lb, 185,96 kg/m)
- average inclination on the length of the string 43,8°
- bit force 49.050 N

Values just from equations regarding Extended Reach Wells should be taken into consideration. Results are shown below:

Motor drilling/non-rotating mode:

K [-]	F_{bit} [N]	$F_{friction-2}$	H_{TVD} [m]	L [m]
0,33	49050	26 249,14	2807,18	3 293,05

Tab. 29. Obtained drill collars' length for Motor drilling / non-rotating mode

Rotary drilling/non-sliding mode:

K [-]	F_{bit} [N]	H_{TVD} [m]	L [m]
0,33	49050	2807,18	1 792,42

Tab. 30. Obtained drill collars' length for Rotary drilling / non-sliding mode

Visual representation is presented on next page.

The graph shows how long drill collars should be in the BHA, in the case, while using motor drilling or rotary drilling.

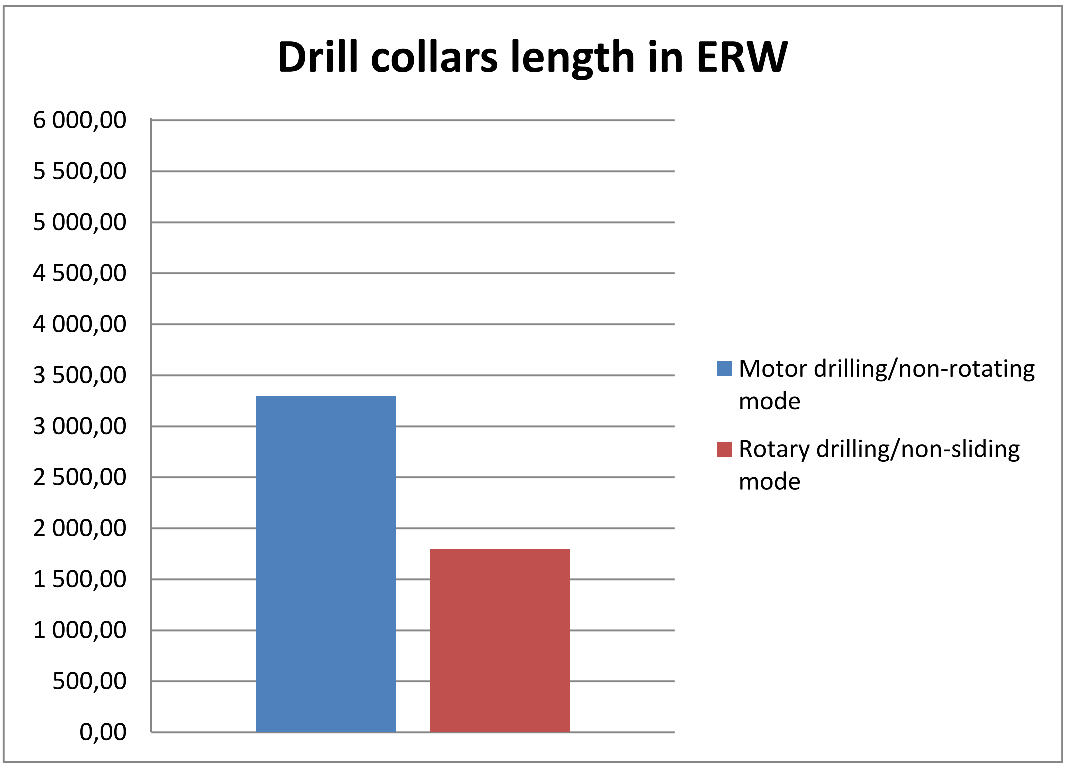


Fig. 67. Comparison of drill collars length for different types of BHA design in ERW

6.7.2 Conclusion

- motor drilling (non-rotating mode) requires really long length of drill collars
- rotary drilling (non-sliding mode) is the one that should be applied
- difference between motor and rotary drilling is as much as 55,57% to rotary drillings advantage
- assumed bit force has huge impact on drill collars length, thus can be recalculated

7. Conclusion

7.1 Selection of the most appropriate pipe

It is very hard to choose just one, the most appropriate pipe, thus two points of view are presented below.

<u>Realistic point of view</u>

It considers use of designed drill string with easily available equipment as well as already contracted semisubmersible unit – Polar Pioneer. The view is oriented for steel (S-135) 5” drill pipe.

<u>Conceptual point of view</u>

It requires importing of equipment and contracting/renting another (different) drilling unit, however provides better performance and possibility of significant cost reduction. The conceptual view is oriented for aluminum (2014-T6) 5” drill pipe.

Conclusions for realistic view point and thereby 5” steel drill pipe:

- great fatigue strength that allows multiple use even in harsh environment
- resistant to high, changeable loads facilitates drilling in harsh environment
- constant endurance limit ensures reliability
- hook load and drag forces insignificant in relation to performance capabilities of Polar Pioneer drilling unit
- great resistance to buckling phenomenon
- good resistance to torque and huge possibility of improvement (i.e. titanium tool joints, double shoulder connection)
- the most cost effective solution
- anticipated great hydraulics with application of 5” OD drill pipe (based on experts opinions)
- huge availability and diversity of sizes that lets select the most optimal solution

Conclusions for conceptual view point and thereby 5” aluminum drill pipe:

- half load on the hook in compare to steel (S-135) drill pipe, thereby it doesn’t require heavy semisubmersible units (lower class of a unit with smaller capacity and capability performance is enough)
- can be very cost effective solution due to lower daily operational costs
- relatively sufficient resistance to buckling phenomenon
- high strength-to-weight ratio
- enhanced corrosion resistance facilitates drilling in harsh environment
- great flexibility allows drilling highly deviated and horizontal wells with satisfactory performance
- non-magnetic body construction affects logging tools in desirable way
- huge possibilities for adapting the pipe to torque requirements (i.e. application of steel or titanium tool joints)

Moreover, both of the approaches can be optimized even more with appropriate application of:

- directional well profile (lower build rate and greater inclinations are advisable)
- drilling mud (heavy Oil Based Mud is recommended)
- suitable Bottom Hole Assembly (in discussed case rotary drilling /non-sliding mode/ should be applied).

To complete the conclusions, the explanation why composite pipes do not exist in the breakdown, is presented.

Composite pipes are not economically justified nowadays. Cost of manufacturing the composite pipe is for now 5 – 7 times higher than a steel pipe with similar size. Furthermore, availability of such pipes is poor, that is why it would require importing of the tubular.

Finally, 3 3/8” composite pipe would cause huge upset in hydraulic performance. Thereby, presenting the pipe in the breakdown had had rather conceptual overtone.

Final summary of realistic and conceptual attitudes is depicted in next chapter.

7.2 Simulation & comparison of ideal conditions

Comparison of hook load, drag force and torque for ideal conditions is shown below. However, it has to be noted that all of the calculations do not take into consideration riser, either BHA loadings.

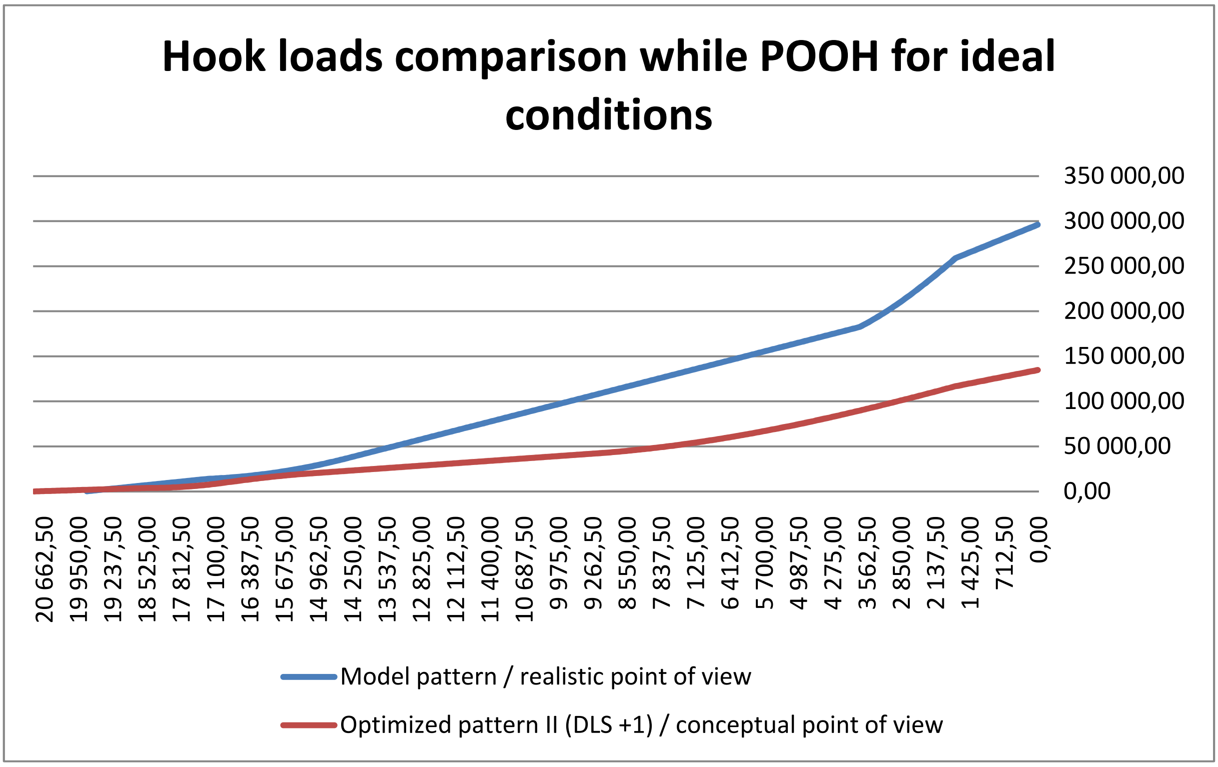


Fig. 68. Hook loads comparison while POOH for ideal conditions

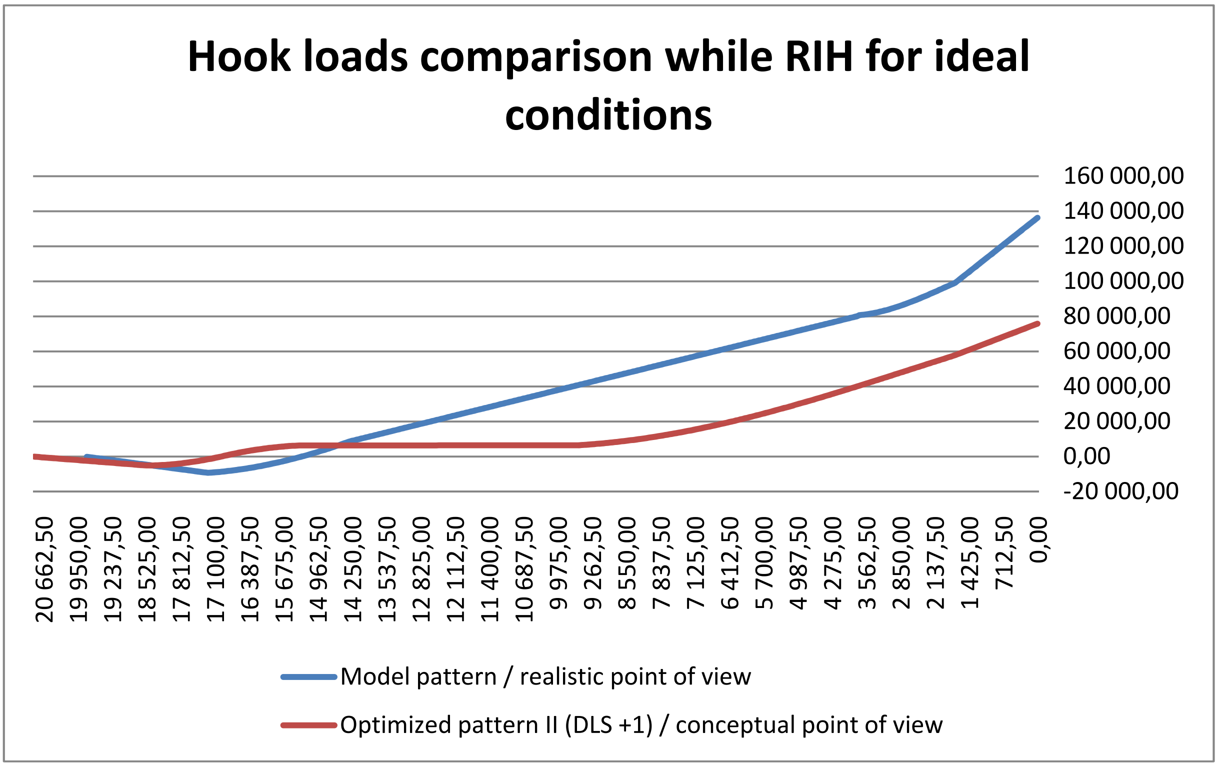


Fig. 69. Hook loads comparison while RIH for ideal conditions

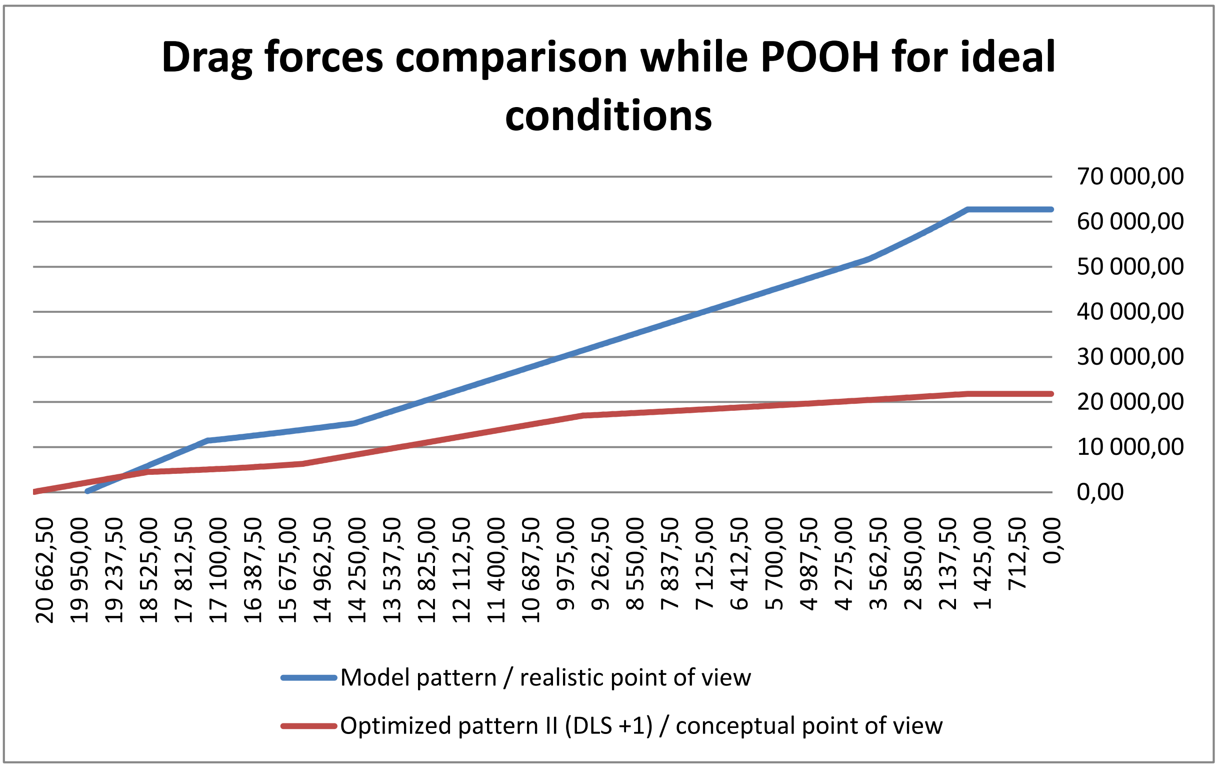


Fig. 70. Drag forces comparison while POOH for ideal conditions

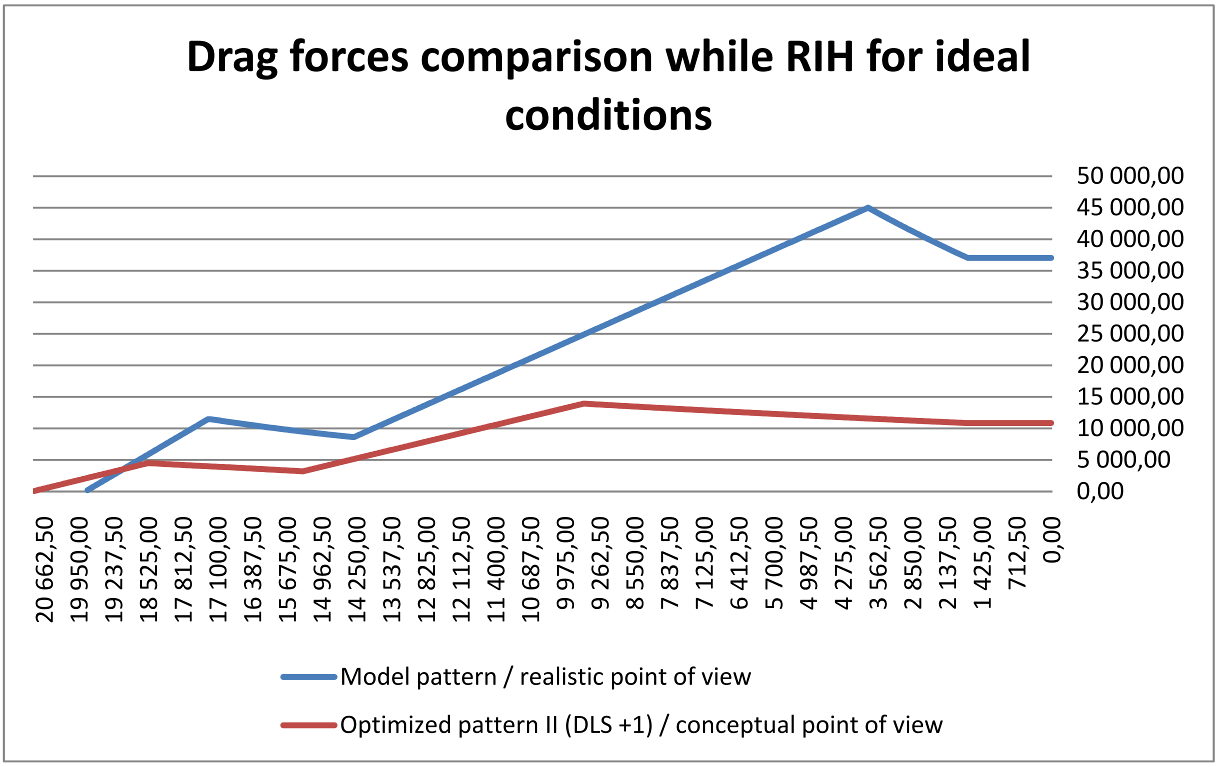


Fig. 71. Drag forces comparison while RIH for ideal conditions

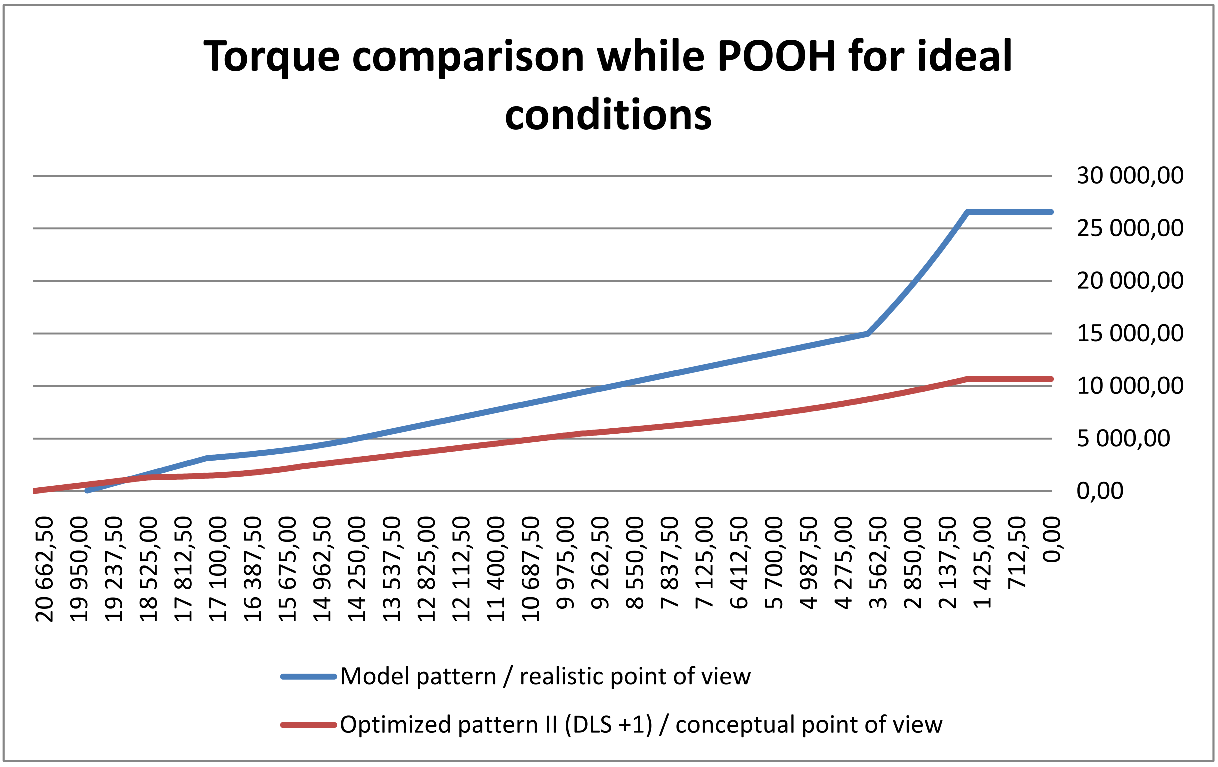


Fig. 72. Torque comparison while POOH for ideal conditions

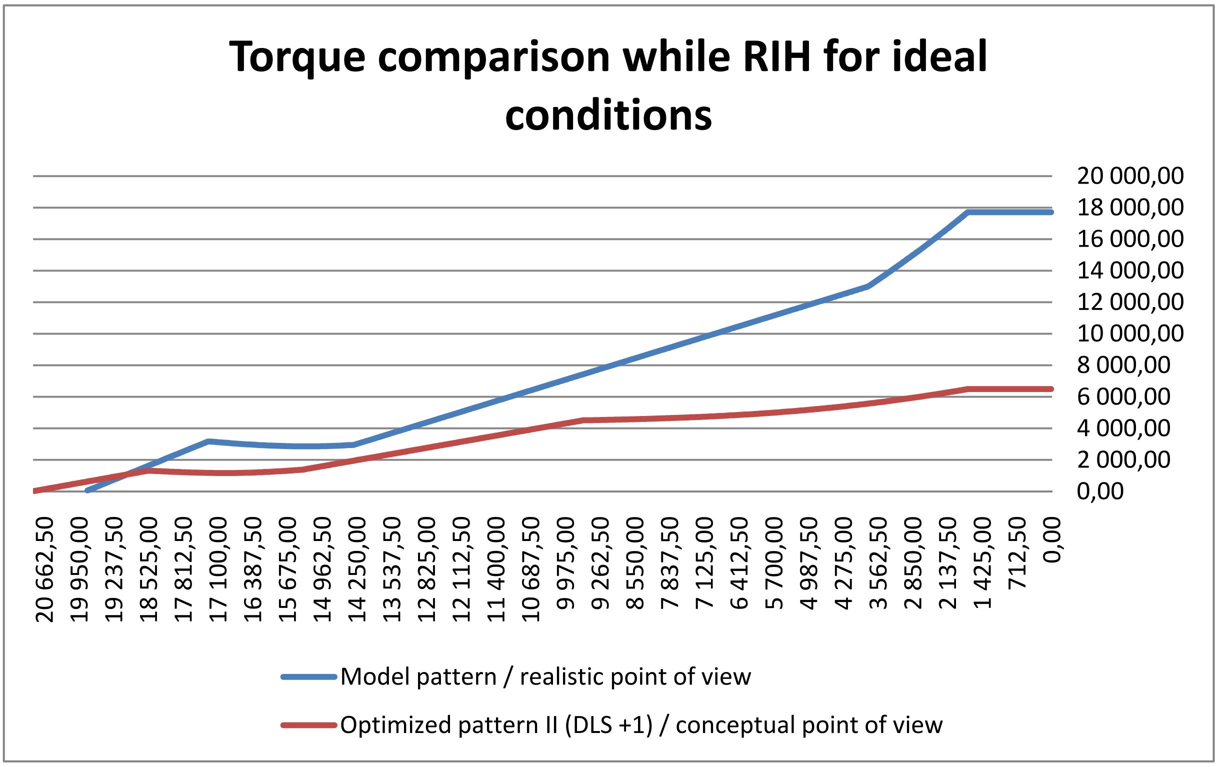


Fig. 73. Torque comparison while RIH for ideal conditions

Summarizing up, even though that application of aluminum pipes involves additional expenses in the very beginning of preparation process and requires huge work, it can be absolutely profitable in the end of the drilling operation.

Moreover, calculated variables such as hook load, drag force as well as torque show how aluminum drill pipes can favorably affect drilling process when it relates to dynamic loadings. Finally, they show how less expenses can be beard while using aluminum drill pipes.

7.3 Final conclusions

- the conceptual well is feasible both with aluminum and steel pipes
- the drilling unit (Polar Pioneer) can handle aluminum, as well as steel drill pipes
- under the present contract conditions it is proposed to perform the operation with steel S-135 5” drill pipes
- steel drill pipes offer larger fault margin while designing/drilling a well for the sake of better mechanical properties
- calculations show that aluminum represents an interesting alternative with attractive hook load, relatively low drag forces and satisfactory torque
- aluminum offers possibility to perform the operation with a significantly smaller rig representing potential for reduced cost and lower execution complications
- composite pipe is not found to represent a realistic alternative at present stage of development, mainly due to high manufacturing cost
- excepting present contract arrangements, aluminum drill pipes are recommended solution on Idun field for the sake of sufficient mechanical properties, excellent strength-to-weight ratio and great development potential in the future

8. Reelwell Drilling Method as an alternative to conventional Extended Reach Drilling

8.1 Overview of Reelwell Drilling Method

Reelwell Drilling Method is a very new solution on petroleum industry market that allows to drill exploration and production wells. RDM enables drilling well sections with harsh conditions such as challenging pressure as well as drilling beyond reach of conventional Extended Reach Drilling.

Three main principles of RDM are to:

- Recover more
- Drill greener and safer
- Save time and money

'Recover more' principle means that it is possible to increase drainage area throw extended reach capabilities. Moreover increased well productivity is expected due to built-in pressure and flow control systems, which reduce formation damage.

'Drill greener and safer' principle indicates use of environmental-friendly drilling mud and improved pressure control that has direct impact on safety and reduced negative-effect in sensitive areas.

Furthermore, the need for additional drilling units and subsea facilities is reduced because of the substantially increased reach from existing units.

'Safe time and money' principle shows that thanks to the solution, it is possible to avoid many drilling problems, thereby reducing Non Productive Time. Factors that make the tool better are first and foremost improved hole cleaning, reduced circulation time and efficient operations.

Main fields of application of the method include:

<u>Mature reservoirs</u>

Reelwell Drilling Method is really attractive especially for Managed Pressure Drilling and Under Balanced Drilling, widely used in mature reservoirs. All that, because the method facilitates pressure management and well control through closed loop fluid circulation system.

<u>Remote reservoirs</u>

Because of the great property of the tool – independent of string weight, Weight-On-Bit – RDM makes it possible to drill much further, pushing present limitations in Extended Reach Drilling.

<u>Running liner</u>

Reelwell Drilling Method facilitates casing or liner installation in the end of drilling process. It can be placed in the end of the horizontal section, with use of RDM hydraulic piston, which works independently of gravity. Then, can be '(…) conventionally cemented in place with no inner restrictions or compromise of hydraulic isolation (…)'.

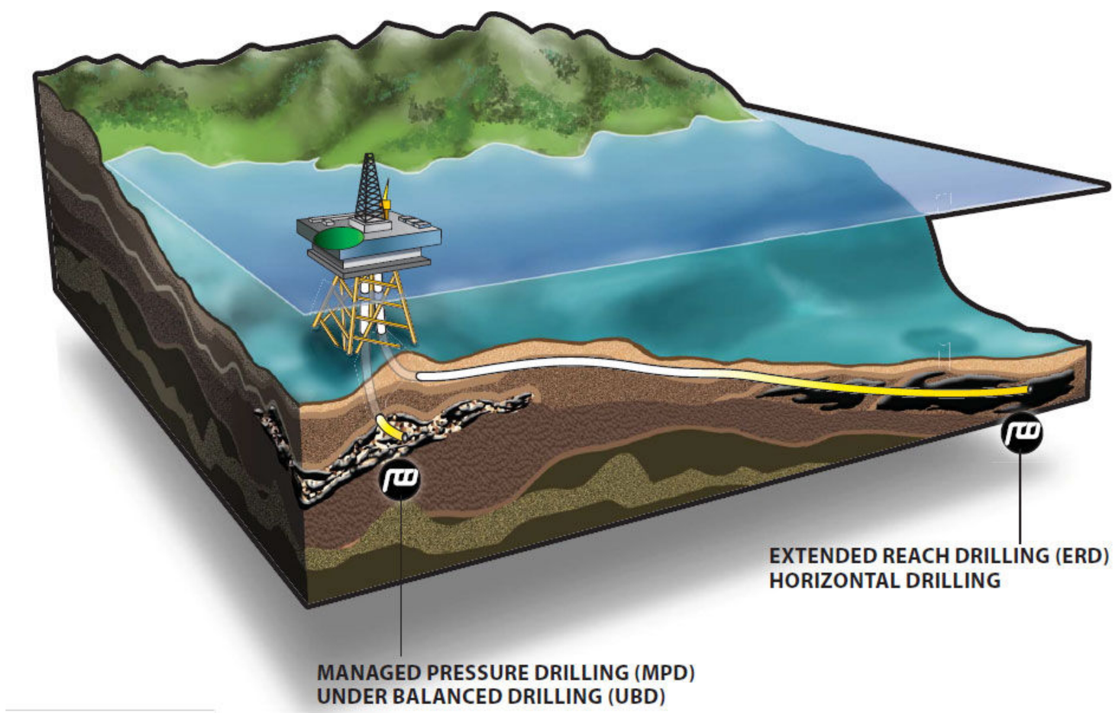


Fig. 74. Reelwell Drilling Method - main fields of application

8.2 Main working principle of Reelwell Drilling Method

The discussed tool is based on Dual Drill String solution that is responsible for transporting mud, down the hole and up, with cuttings, to mud treatment & pump system. Other key components that will be talked over include especially FCU (Flow Control Unit), TDA (Top Drive Adapter), UAC (Upper Annulus Control Unit), Hydraulic Piston and DFV (Dual Float Valve).

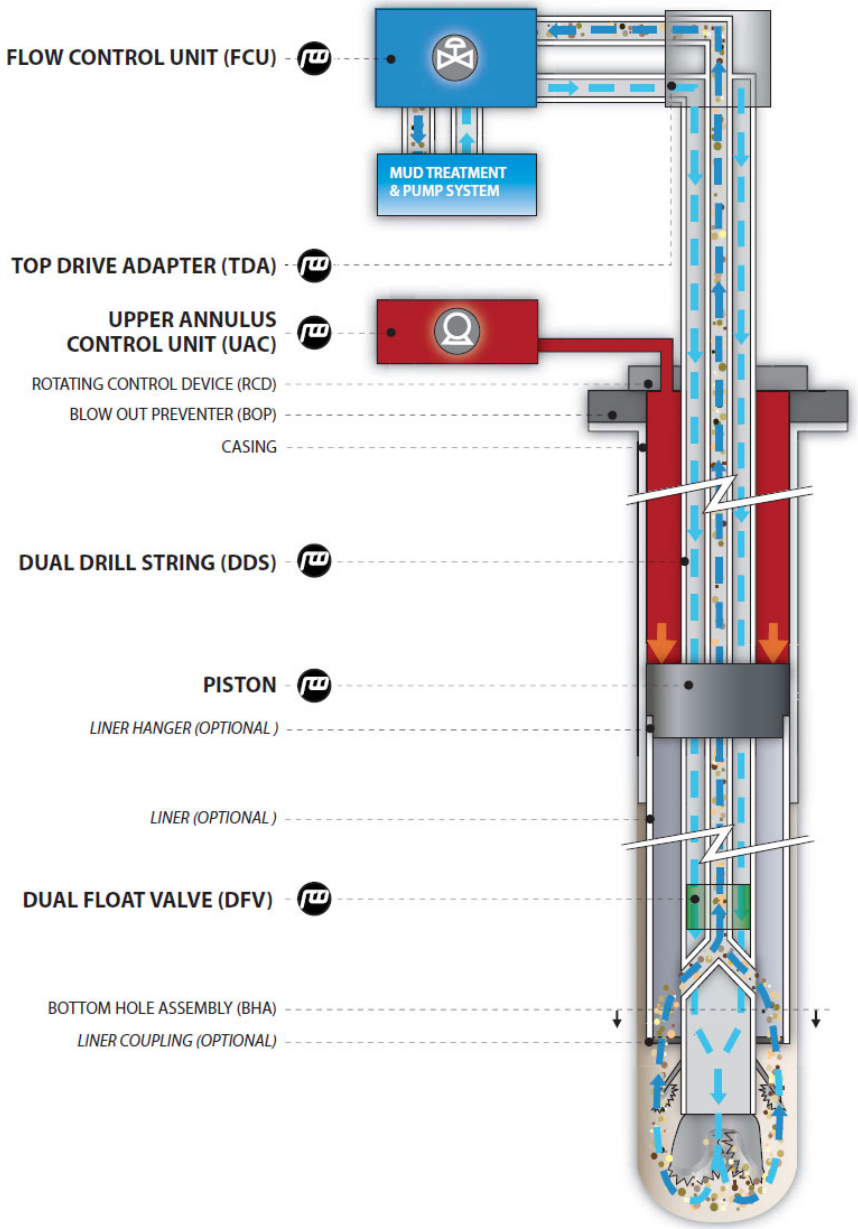


Fig. 75. Reelwell Drilling Method - main working principle

Description of the main elements of the tool (from the top):

FCU (Flow Control Unit):

Flow Control Unit is a control valve arrangement. All active drilling fluids go throw the unit. The main task to be performed is to provide constant down-hole pressure while drilling and pipe connection. Moreover, the unit has flow and pressure sensors on the inlet and outlet, as well as computer that measures and monitors the present status of the well.

Fig. 76. RDM - Flow Control Unit

Fig. 77. RDM - Top Drive Adapter

TDA (Top Drive Adapter):

Top Drive Adapter is a dual conduit swivel. It allows rotation of the drill string. It also includes power and data transmission units.

UAC (Upper Annulus Control Unit):

Upper Annulus Control Unit is a kind of pumping unit. The main task of the pump is to provide constant pressure in the annulus, between the hole and the Dual Drill String, behind the piston. Therefore, UAC indirectly helps to provide Weight-On-Bit while drilling.

RCD (Rotating Control Device):

Standard Rotating Control Device has been used. It has been `borrowed` from Weatherford Service Company.

BOP (Blow Out Preventer):

Standard Blow Out Preventer has been used to secure drilling process.

Casing:

Standard casing pipes have been used in Reelwell Drilling Method.

DDS (Dual Drill String):

Dual Drill String is a key component of Reelwell Drilling Method. It is a closed loop flow circulation system. Drilling mud is transported down the hole throw Dual Annulus, which means the annular space between pipe and inner string. Then, after cooling down the bit and removing cuttings, the mud is transported throw the inner string, up to the surface. The wellbore remains relatively dry and clean.

Fig. 78. RDM - Dual Drill String

Fig. 79. RDM - Hydraulic Piston

Hydraulic Piston:

Hydraulic Piston is the unit, which prevents loss of annular well fluid, to under-pressured formations. However, the most important property of the Hydraulic Piston is the fact that it provides Weight-On-Bit, even in highly deviated or horizontal wells. Thus, it makes it one of the key components of the tool.

DFV (Dual Float Valve):

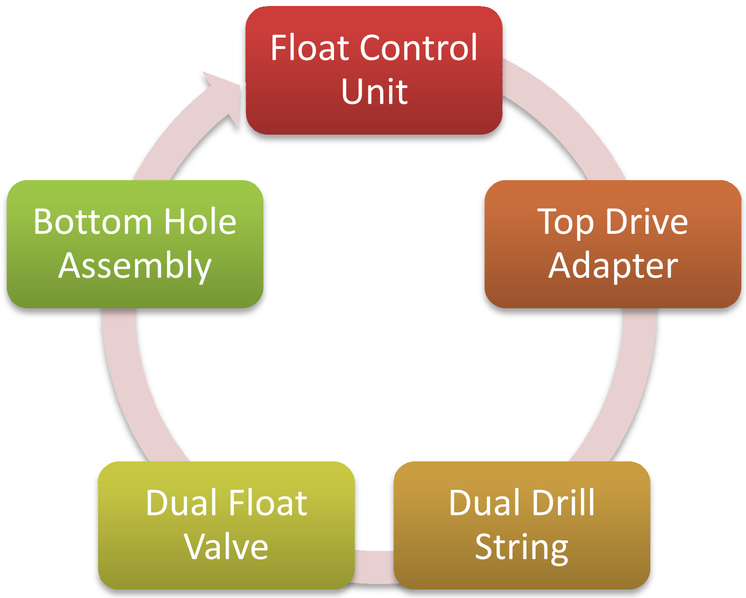
Dual Float Valve is responsible for down-hole pressure isolation. Moreover, it facilitates controlled pressure drilling and pressure-less pipe connections. In reality, it works the same as regular valve. However, there is one difference. I doesn`t block just the flow from upper to lower part of the hole, but conversely as well, it blocks the possible flow from lower to upper part. When the pressure above the valve is equal to the pressure below, then Dual Float Valve is unblocked and ready to operate.

Fig. 80. RDM - Dual Float Valve

BHA (Bottom Hole Assembly):

Standard Bottom Hole Assembly is used in Reelwell Drilling Method. However, sometimes a reamer is used, when necessary, for example to facilitate liner drilling.

That is how it works:



Drilling fluid starts its 'journey' from Flow Control Unit, where it is prepared.

Then, it goes down throw Top Drive Adapter, Dual Drill String until it reaches Dual Float Valve.

There, in X-crossover tool (part of Dual Float Valve) the flow is divided and gets to bit area. The bit is cooled down and the cuttings are removed.

In the next step, cuttings with drilling mud get into Inner String and travel the same way as they have arrived, which means throw Dual Drill String, Dual Float Valve, Top Drive Adapter until they reach Flow Control Unit with mud treatment & pump system.

Circulation flow path

The main difference between Reelwell Drilling Method and conventional Extended Reach Drilling is, as we can see above, the circulation flow path of the drilling fluid.
In conventional drilling, mud is pumped throw drill pipes down to Bottom Hole Assembly and it gets back throw annulus, space between drill pipes and a wellbore or casing. In Reelweell Drilling Method, mud is pumped throw Top Drive Adapter and Dual Drill String (annulus of DDS) until it reaches the assembly down the wellbore. Then, it goes throw inner string to the surface. The RDM solution can remind reverse circulation method, however the whole process is done in the Dual Drill String, the drilling fluid doesn't have any contact with a wall of the well.

The discussed internal circulation provides several advantages, such as:

- high start up ECD (Equivalent Circulation Density) is prevented
- possibility of change of active fluid, whilst having an isolation from open hole section
- faster remove of cutting from the system

The last component, which is worth describing, is Hydraulic Piston. It provides hydraulic force on the bit, thus is really advantageous while drilling highly deviated and horizontal wells. The force is created by the fluid placed behind the piston, but in the front of RCD (Rotating Control Device), in the annulus between DDS (Dual Drill String) and casing. The fluid is pressurized, thereby creating hydraulic force.
There is an option as well, to use liner while drilling. In this case, the piston is placed directly behind the liner.

8.3 Theoretical comparison of Reelwell Drilling Method vs. Extended Reach Drilling

Reelwell Drilling Method is distinguished by a few factors:

- hydraulic piston providing Weight-On-Bit (theoretical calculations proved that it is possible to reach 20km of Measured Depth with the method)
- superior cleaning obtained by application of Dual Drill String solution
- accurate pressure control
- possibility of lining while drilling

The mentioned-above factors make Reelwell Drilling Method more effective solution than conventional directional drilling. Moreover, in some cases, it is cost effective tool.

Challenges and main differences between RDM and conventional ERD are boiled down to two categories:

- Extended Reach Drilling
- Managed Pressure Drilling

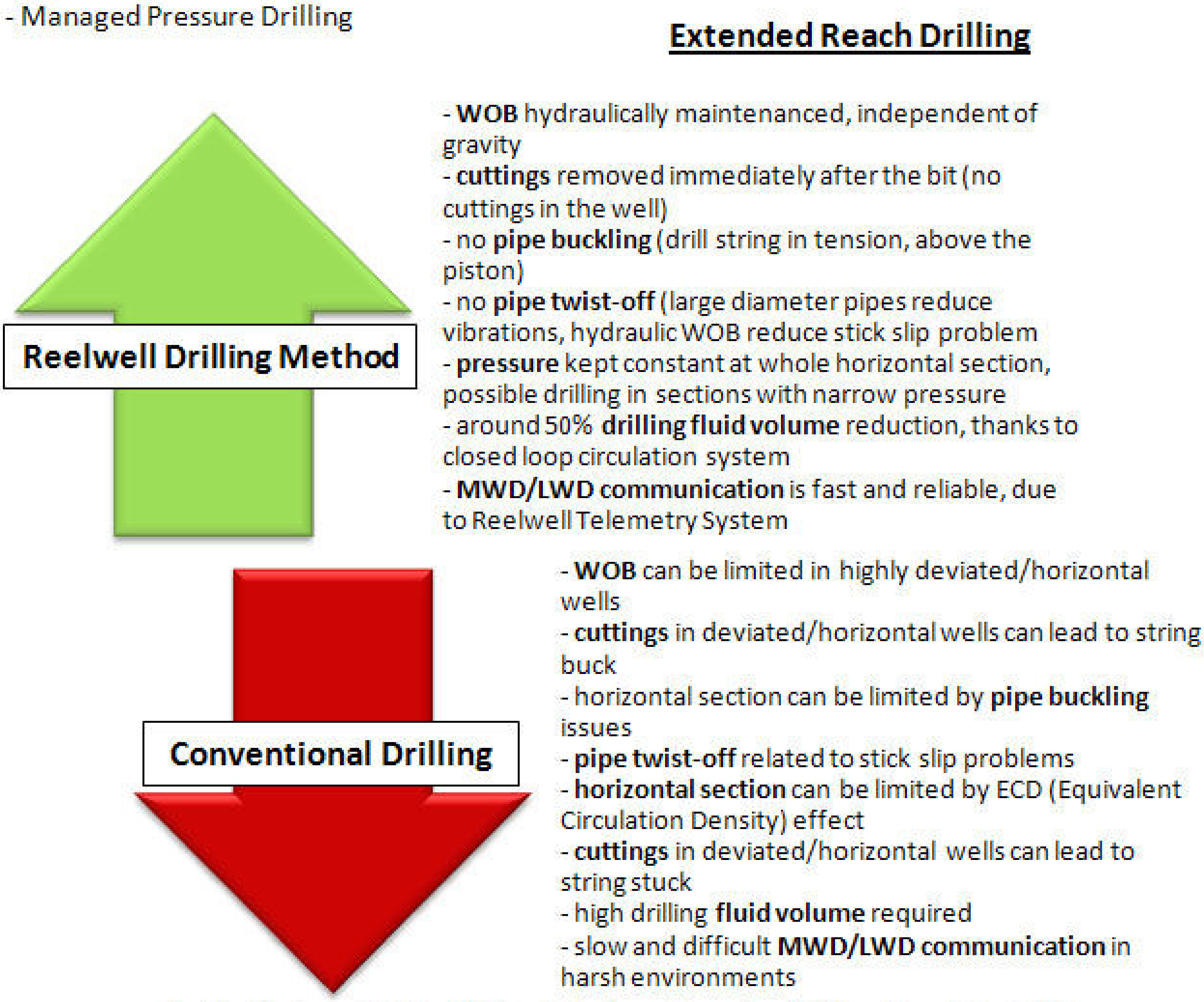


Fig. 82. Advantage of Reelwell Drilling Method over Conventional Drilling when relates to ERD

Managed Pressure Drilling

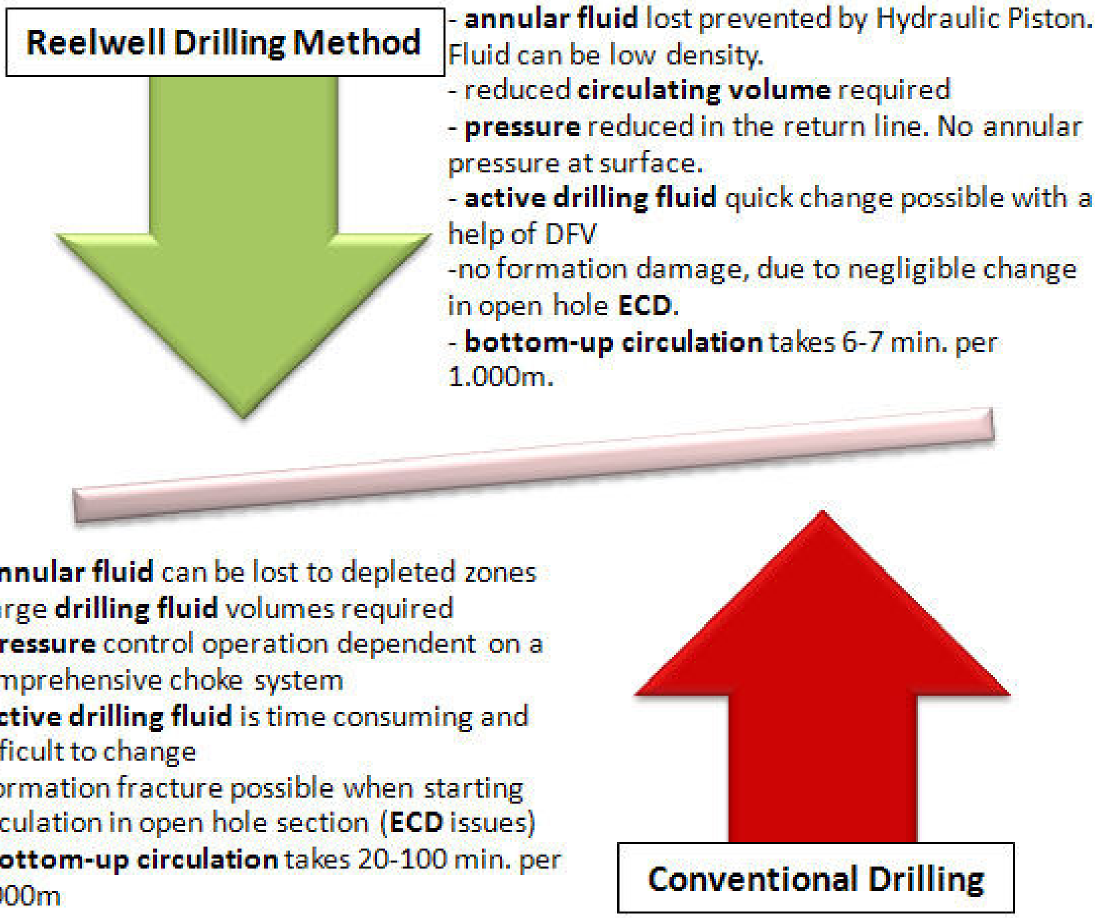


Fig. 83. Advantage of Reelwell Drilling Method over Conventional Drilling when relates to pressure control

8.4 Advantages of Reelwell Drilling Method

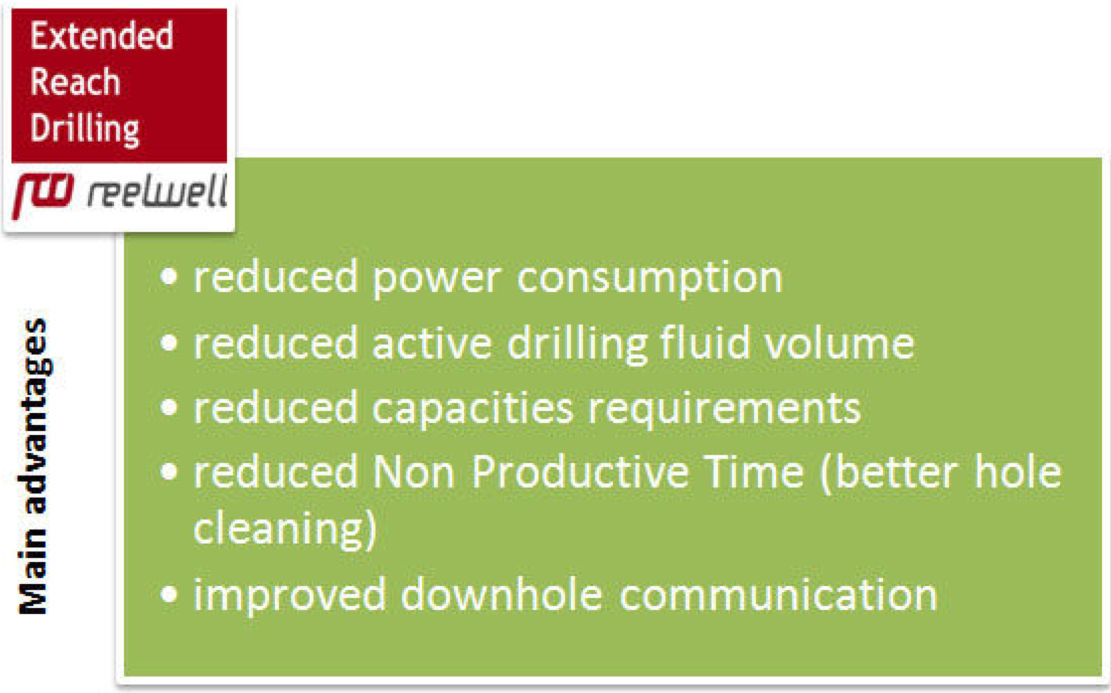


Fig. 85. Reelwell Drilling Method - Main advantages

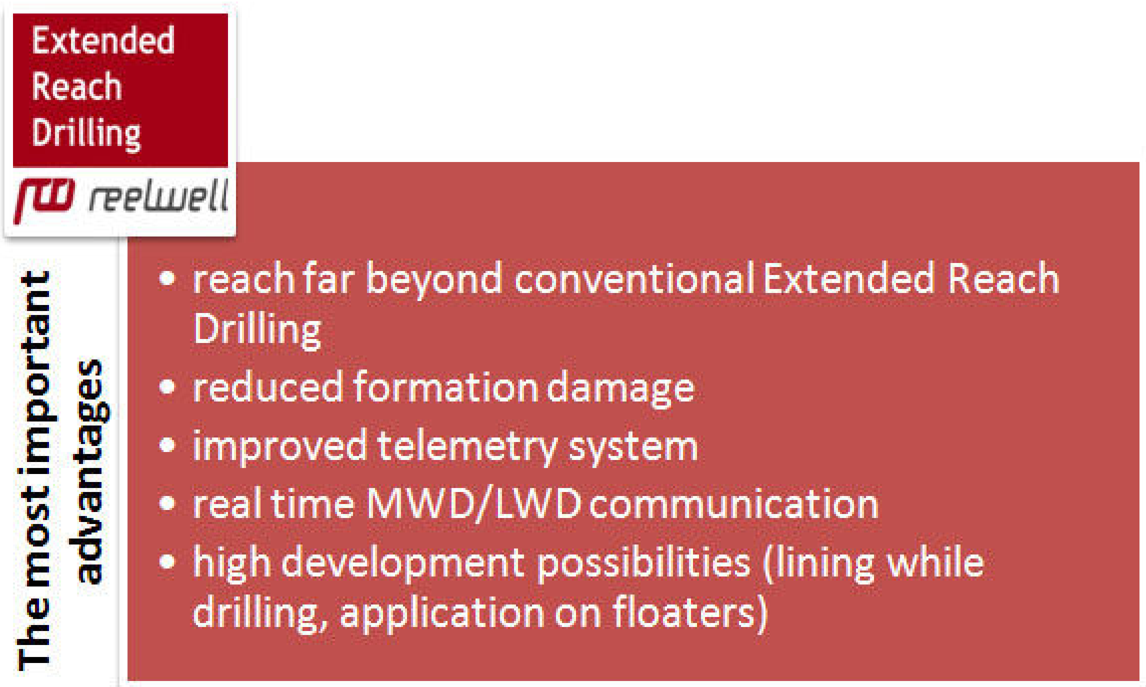


Fig. 84. Reelwell Drilling Method - The most important advantages

VIII Nomenclature

POOH	Pool Out Of Hole
RIH	Run In Hole
DLS	Dog-leg Severity
KOP	Kick-Off-Point
BHA	Bottom Hole Assembly
OBM	Oil-Based Mud
WBM	Water-Based Mud
A&M	Air & Mist
MWD	Measure While Drilling
LWD	Logging While Drilling
TVD	True Vertical Depth
MD	Measured Depth
ERD	Extended Reach Drilling
ERW	Extended Reach Well
FCU	Flow Control Unit
TDA	Top Drive Adapter
UAC	Upper Annulus Control
DDS	Dual Drill String
DFV	Dual Float Valve
RCD	Rotating Control Device
BOP	Blow Out Preventer
ECD	Equivalent Circulation Density
θ	plane inclination angle
W	buoyed weight of a pipe
T	axial tension
T_n	tension at the top
T_{n-1}	tension at the bottom
μ	friction coefficient
F_r	resultant normal force

I_c	critical inclination
ΔI	change in inclination over ΔL
ΔA	change in azimuth over ΔL
$I_{(avg)}$	average inclination over ΔL
E	Young's modulus
I	moment of inertia
ρ	pipe weight
A	cross sectional area of a pipe
g	acceleration due to gravity
r	radial clearance between the outside diameter of a pipe and a hole wall
M	torque of a segment ΔL
R	outside radius of a pipe
α	inclination angle
β	buoyancy factor
w	unit weight element
w_1	unit weight of a drill collar
w_2	unit weight of a drill pipe
ΔL	length between survey points
P_{cr}	critical force that initiates buckling
L	pipe length
L_{BHA}	Bottom Hole Assembly length
n	order of buckling
K	factor that determines type of buckling
f_o	normal force that takes into account wellbore curvature
ρ_{mud}	mud density
ρ_{pipe}	pipe density
F_{bit}	bit force
H_{TVD}	True Vertical Depth
$F_{friction-1}$	frictional force from drill collars
$F_{friction-2}$	frictional force from drill pipes

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X Appendix