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Abstract

Unlike the conventional well technology, slim hole uses a relatively narrower well size. The concept has been introduced long, but the application in petroleum well not very common. Based on its advantage in terms of cost, there is a possibility to use it for petroleum well and geothermal wells.

This thesis evaluates the slim hole drilling method with the objective of investigating how far one can drill. For this, the thesis work considers three qualification operational conditions. These are drill string mechanics (Torque, drag & Stress in drill string), hydraulics and cutting transport efficiency. The method of analysis flow chart is presented in section § 6.2.

Using this method, two slim well structures obtained from Kuwait, and Carter Creek Field were analyzed. In addition, an ultra-deep slim-hole scenario also designed and analyzed.

Based on the evaluation of considered designs, the feasible slim well design presented in three categories:

- Shallow-slim well (up to 13000ft) can be drilled with low grade E-75
- Deep-slim well (16000 ft) can be drilling with a combination of (E-75 and G-95) Grades
- Ultra-deep slim well: (20000 ft) can be drillied with high grade, S-135.

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Nomenclature

A	area
F	force
g	gravitational constant
P	pressure
K	consistency index
P_a	Annulus pressure
T	Torque
ΔT	Increment torque
W	weight
α	Azimuth
β	Buoyancy factor
θ	Inclination
σ	Normal Stress
σ_y	Yield strength of pipe
μ	Fluids Viscosity, Pa.s, mPa.s or Cp
ρ	Density, SG or kg/m^3
τ	Shear Stress, Pa
τ_0	Yield Point/ Stress, Pa

Subscripts

i = inner
o = outer
r = radial
a = axial
n = normal

Abbreviations

API	American Petroleum Institute
BPX	British Petroleum Exploration
Cof's	Coefficient of Friction
ECD	Equivalent Circulating Density
FF	Friction Factor
H-B	Herschel- Buckley
HPHT	High pressure High temperature
IEA	International Energy Agent
NCS	Norwegian Continental Shell
POOH	Pull Out Of the Hole
RIH	Run Into Hole
ROP	Rate of penetration
SHD	Slim Hole Drilling
SPE	Society of Petroleum Engineers
SHCT	Slim Hole Coiled Tubing
PV	Plastic Viscosity
SF	Safety Factor
YP	Yield Point, Pa
TD	Target Depth
T&D	Torque and Drag
TVD	Total Vertical Depth
WOB	Weight On Bit
YP	Yield Point

1 Introduction

This thesis presents an evaluation of slim well in order to investigate its application for geothermal and for petroleum well. The analysis was based on several drilling operation, namely mechanical, hydraulics and cutting transport issues. Simulations well were built based on Kuwait (slim hole well design) and Carter (slim hole well design) wells. In these wells, several simulation experiments were carried out in order to select the right quality of drill string. The problems related to the low grade strings are attached in appendix. The solution with high grade is presented in the main report. For the analysis, Wellplan/Landmark and Excel implemented models were used.

1.1 Background

The world demand for energy is increasing, and fuel fossils seems has risen to global prominence. The term energy source covers major fossil fuels such as (Petroleum, coal and natural gas), as well as nuclear and hydropower and other renewable energy resources**. Figure 1.1:** shows predicted growth of primary energy consumption by fuel from year 2003 to 2030. The estimates of all energy types have been expected to be a significant growth of 30 %(nuclear) and 95 % (coal) during this period.

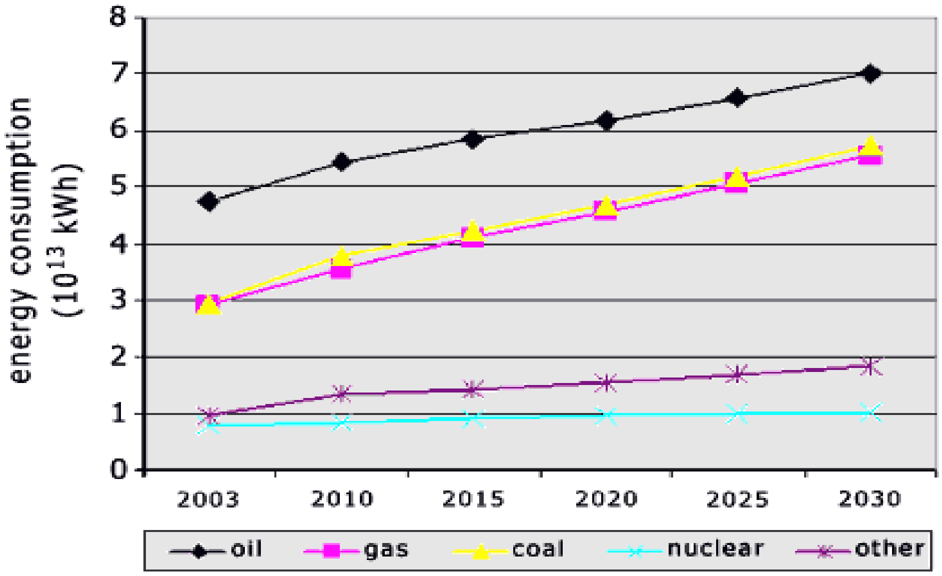

Figure 1.1: *World consumption growth of primary Energy from 2003 to 2030 [1].*

It is been thought that the temperature will rise if this continues to increase, resulting a greenhouse effect. As we know that today and the next several years will be facing global warming. This is a great concern due to the huge impact on environment and humankind such the rise of sea levels in the coastal areas. Due to this matter, there are currently increase efforts to switch the major energy sources such as fossil fuels (coal, petroleum, natural gas) to renewable energy. The latter group consists of the contribution from geothermal, solar, wind and biomass energy sources. Even though, the renewable energy source is expected to provide around twice the contribution of hydro by 2030 increasing by a significant percentage. There is still projected to provide around 7% of the total energy to make it serious alternative. At the same period, the fossil fuel consumption is projected to increase massively **[1].**

For these reasons, the energy demand and supply will be causing to rely more and more energy import over the next several decades which will ultimately drive the energy cost up to a point where it will have a huge impact overall competitiveness to all countries. According to the International Energy Agent (IEA), it is estimated that over & 700 billion in capital investments will be made through 2035 to meet the meet the primary energy rising demand requirements in the years to come **[2].**

It becomes an increasing concern on the challenges that the oil industries will face to cope the rising needs for fossil fuels. With the current conditions where there will be an increasing number of wells to be abandoned due to the large number of oil fields that are already no longer producible or profitable as reaching at the end of its life cycle. This, coupled with the maturing areas where margins are declining and the number of new giants oil fields are extremely becoming difficult to discover. Most of the new discoveries tend to be smaller fields that are often not economical to exploit them. This suggests that it will become extremely difficult maintaining an economic global oil reserves at a desirable level once oil prices become higher.

Therefore, the oil industry are seeking new technologies to overcome operational and cost challenges that help to drill more efficient and cost effective way. Since the need to reduce capital budget under current economic condition in the oil companies become more critical due to such as the high cost of the day rate hiring a drilling rig and other costs associated with equipment. We can say that the oil industry want to make great effort to reduce the drilling costs such as by drilling wells as a small as possible. In recent decades, the petroleum industry is moving to more remote areas of the world for exploration activity. The transportation to this remote locations becomes much more difficult to reach and expensive due the time consuming of the equipment transportation. In this climate, slim hole drilling technology is proposed as a method that significantly reduces the cost of transportation and equipment. This can be achieved because of the use of smaller drilling rigs and/or workover rigs, easier equipment mobilization, reduced casing size, minimized drilling waste and smaller equipment. Therefore, slim hole drilling is becoming more accepted as viable drilling method especially to reduce capital investment in exploration activity.

Since rising development costs are one of the major problems facing the oil companies today. The recent efforts by the companies is to design several new concepts to improve drilling techniques. Among the ideas, the use of slim hole technique is proving to be the most cost effective. The technique has been experimentally applied within the industry to evaluate its significance as cost reduction measure. The results showed a significant reduction in overall drilling cost for exploration and development oil fields.in comparison with conventional drilling, slim hole wells indicated a significant cost reduction of 30-40% range for exploration and appraisal wells and 30-40% for injection and production wells. This advantageous savings is achieved by variety categories including less site preparation, rig rate and time, tubulars, mud, cement and even environment. The Carter Oil Co. had drilled 108 slim hole wells documenting with an estimated savings of $ 162,000 below the cost which would have been incurred with conventional sized holes. With the performance of modified slim hole program, the slim hole technique resulted 8 % less penetration rate and 5 % reduction a bit life than conventional **[3].** Furthermore, slim hole practice are most applicable in conventional wells where unexpected problem may occur such as a lost circulation or differential sticking that might lead to plugging and abandonment or sidetracking of the well. Slim hole drilling technique with the permit selection of the optimum sized slim hole rig allows that the well can be drilled further and all the way down the target depth.

In some horizontal wells that could otherwise be unprofitable to develop with conventional drilling. Today's improvement of equipment, technology and economic has made possible to change this scenario as compared to earlier times. Slim hole drilling provides the re-entering of the existing wells has been a boost to the development of horizontal drilling. It has provided the opportunity to effectively develop new reserves, access by passed oil and convert the existing wells to horizontal wells **[4].** New technology such as geosteering technique made possible for the drillers to accurately steer downhole equipment and bits to stay within pay zones and reach the target. The use for a smaller diameter wellbore to replace the larger wellbores where there is limitation to drill deeper regarding to casing design can slim hole technology help the industry to reach this goal. Slim well technology can handle this with no limitation of how further a well can be drilled, even if some well problems occur during drilling.

However, it is important to evaluate problems relating to torque, drag, stresses and friction losses in drillstring when the well becomes ultra-deep.

As the environment becomes more and more focused area in the petroleum industry. The goal is to improve working condition (HSE) such as to have zero accidents and to be as environment friendly as possible in order to reduce environmental impact. To be able to reach this goal, the oil companies needs new technology that minimizes environmental issues such as pollution. One way to achieve this goal is the use of slim hole drilling technique that requires smaller drilling rigs, minimize drilling wastes, and reduce noise and air pollution and less transportation for mobilization and demobilization of drilling equipment.

Since the introduction of slim well technology, one of the application is in shallow well exploration well- however due to its cost and simplicity, it could have a potential for geothermal well. It is therefore an important to evaluate the application of slim well for petroleum well and for geothermal wells. This thesis is going to analysis these issues.

1.2 Problem formulation

As mentioned earlier, this thesis is going to generate realistic case scenarios in petroleum and geothermal wells. Therefore, the issues to be addressed in this thesis are:

- How far we can drill in vertical and designer (any inclined) well geometry with slim hole?
- How is the hole cleaning phenomenon in ultra-deep and shallow slim hole?
- How is the hydraulics in slim well?

1.3 Objective

In order to answer and evaluate the issues addressed earlier, this task of this thesis is:

- To review the slim hole drilling technology
- To review theories for the analysis of slim hole drilling technology
- To perform simulation studies based on the reviewed theories such as:
    - torque, drag and stress in drill string
    - cutting transport simulation
    - hydraulics simulation

1.4 Structure of the thesis

In chapter 1 introduction of the thesis will be given as the background, problem formulation, the objectives and the report structure of the thesis.

In chapter two work published in the open literature of slim hole drilling will be reviewed.

The theory behind the simulation study of torque, drag, stresses, hydraulic and hole cleaning is treated in chapter 3.

Several simulation studies for the qualification of drill string mechanics for a given operational conditions will be analyzed in chapter 4. Of particular interest of torque, drag and von-misses would be analytically examined which can be critical to the success of slim wells.

In chapter 5, the study of pressure losses in the narrow annulus in slim wells due to high annular pressure will be presented by using Unified hydraulic model. Besides that, cuttings transport would be simulated of comparing conventional and slim hole drilling.

In chapter 6 contains general observation of the results obtained from literature review and chapter 4-5 will be briefly presented.

In Chapter 7, the main conclusion of this thesis is treated.

2 Literature study on Slimhole Drilling

This chapter presents the literature study on slimhole drilling technology along with benefits and applications.

2.1 Introduction

In the oil and gas industry, wells can be intended to drill in many different ways to serve multiple purpose depending on the design and operators requirements. Since there is high demand in the oil world and the technology is emerging with pace, the current trend is to drill wells in cheaply, safely and more efficient manner. This can be achieved by developing new types of wells that can lead to in a more cost effective way. For instance, slim hole well which can minimize the drilling cost and risk and may help cut the rig time that can lead to an increase the recovery rate. Therefore, the concept of smaller size hole have the possibility to offer for smaller drilling rig with potentially smaller surface area. In addition, it offers reducing the required for mud and cement volumes, with required smaller reserve mud pit.

There is an improvement in equipment and the technology but still the petroleum industry needs to minimize the cost of drilling with more difficult wells such as deep wells, HPHT wells. Advance technology means that we can recent safely drill new wells with small diameter and with minimum borehole problems.

Despite the development of the new technologies, still some studies shows that there is an increase in well cost. Referring to **Figure 2.1,** illustrates the dramatic increase in well costs for 8 field on Norwegian Continental Shelf (NCS). The presentation states that the well costs on fixed installation have doubled in a last six years. In addition, mobile drillings units doubled the costs at the same period **[5].**

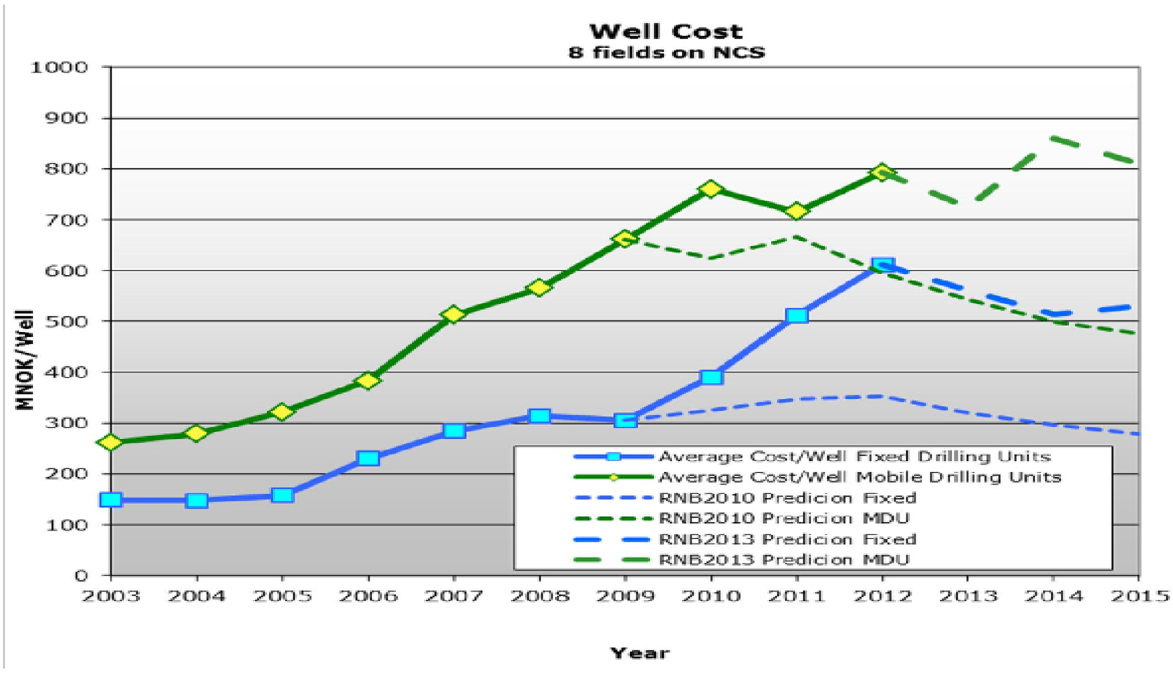

Figure 2.1: *Well costs for 8 fields on NCS within the period 2003 to 2015 [5].*

Therefore, the need for more cost effective wells has been a vital factor to consider in well planning. With the current trend towards an emerging technology, "slimmer" wells can be simple and better in economy which can be proven to be sound and successful in proper application, reducing the well cost. Because of operational problems such as drill pipe performance, poor bit, high ECDs and standpipe pressures resulting from inappropriate mud system, the gross progress per day reduced with the sizes below 7-7/8 is showed in **Figure 2.2.** Furthermore, a lack of understanding of the drilling process led to cumulative operational problems **[6]**.

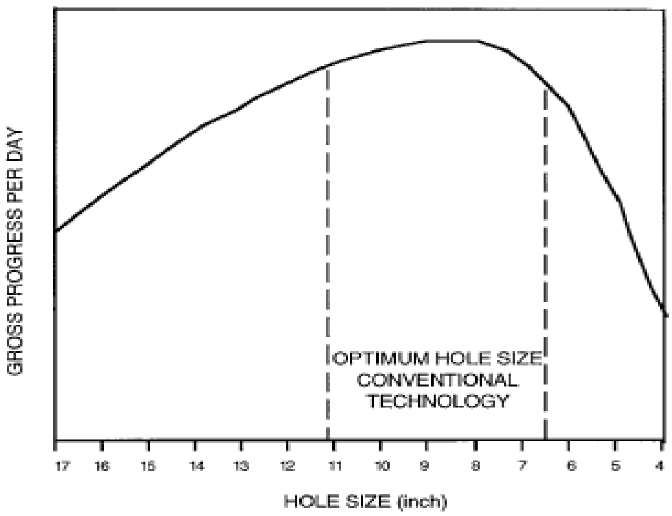

Figure 2.2: *Effect of hole size on overall drilling efficiency [6].*

2.2 Slim hole drilling regards to conventional drilling

Typically, definition of slim hole drilling means different thing to different people. However, some companies refer to as reduced number of casing strings when they design production wells. This involves eliminating the need for a second set of BOPs that further reduced the volume of rocks drilled. For instance, in its North Sea forth field, BP Exploration Co, removed the 20-inch casing string. This resulted of 30 to 40 percent well cost reduction over the 15-well program that has been investigated by using the same conventional equipment. The major reason for pursuing slim hole drilling concept is that one of the most development cost effective methods in oil and gas field **[7]**.

Generally, a slim hole is defined as the drilling of a well with a diameter less than that used on conventional wells **[8]**. By analyzing more on this type of drilling, one may conclude that there will be improved well designs compared to the traditional drilling. The increased focus to maximize the profitability of new drilled wells can significantly lead to cause slim wells to become the opportunity for the petroleum industry to cut drilling and completion costs. The following **Table** 2.1 makes comparison between slim hole wellbore and conventional wellbores. For those wells which are designed with lateral wellbore diameters that are greater than 8 in will be referred to conventional wellbores. While for those wells with hole size that is less than 6 inch will be called “Slim hole “wellbores **[9].**

Table 2.1: *Comparison between conventional and slim of Lateral Hole Designs [9].*

ITEM	CONVENTIONAL Hole Design	SLIM Hole Design
Lateral Diameter	8,5 inch	3,875 inch
Build Rates (Degree\100)	10-12	16-20+
Radius of Build (Feet)	573-477	358-287
Casing designs		
Surface	13,375 inch	8,625 inch
Intermediate	9,625 inch	4,5 inch

Recent development of materials and advance technology that allow drilling, completion, and production operation has made possible for the use of slim hole drilling in the petroleum industry. This drilling technique is becoming more accepted as more instruments are developed and built to accommodate the use of small hole diameter. Therefore, the method will viable to both deviated and horizontal drilling operation due to it is principle advantage: reduced cost **[10]**.

For instance, one thousand feet of casing for 12 ¼ inch hole weighs 59 tons while the equivalent length of 8 ½ in hole casing weighs about 29 tons and the steel is priced by the ton. Several other items such as drill bit, drill pipe, mud chemicals, cement and cuttings cleaning budgets become smaller. Due to the scaling down the hole diameter, the overall size of the required drilling rig, its lifting capacity and its footprint can be minimized. Because of the reduction of diameter, there is loss of torque transmission capability that requires compensatory application of higher rotation rates than are commonly used in conventional drilling. in the end, the time to reach the TD is cut down as a smaller diameter hole is usually faster to drill, all other factors being the same **[10].**

2.3 Current technology in Slim Hole Drilling

Currently, new drilling technologies have been developed for smaller diameter wells that has a considerable benefits over the conventional method in terms of application. Their results are in substantial advantages over the traditional drilling, for instance reducing the well cost and risk, increasing of drilling rate that further can lead to increase of drilling efficiency and is more environmentally friendly. This includes:

- Slim hole Coiling tubing
- Continuous coring method
- Down sized conventional drilling

2.3.1 Slim Hole Coiled Tubing Drilling

Slim hole coiled tubing (SHCT) is one of the new drilling technology over the last 10 years. It combines slim hole technology with coiled tubing technology which has a large number of advantages as compared to conventional drilling technique in a certain applications. In addition, SHCT has the potential to reduce the drilling cost and risk and remarkable potential applicability. This typical applications for slim hole coiled tubing include: **[11]**

- Exploration wells where 4-D image of recoverable hydrocarbon and unrecoverable can be acquired and monitored with the ideal depth, without disturbing development or injection.
- In a shallow well, it has notable benefit, the space and load is only 1/3 of conventional drilling technology.

- Oil well re-entry. SHCT provides a means of improving recovery by vertical injection and porosity of different horizontal level can be obtained by seismic prospection system.
- As this new drilling technology is progressing and more downhole tools have been developed in the coiled tubing industry. Drilling deep wells in existing well with extended slim hole section, reservoir can be evaluated more economically with slim hole coiled tubing and the pay zone is more easier to approach.

2.3.1.1 Potential benefits of slim hole coiled tubing technology

The potential advantages that involve this new technology include: Comparing to the traditional drilling, SHCT can decrease drilling time, reduce material and equipment resulting to reduced drilling cost.

The use of these technology is expected to minimize the cost by 1/5 in drilling, 1/3 in exploration and ½ in development. According to Department of energy (DOE) in US, the development of SHCT can lead to the increasing of production in shallow well(less than 1500 m) up to 350 $\times 180m^3$. In addition, the method reduced the environmental impact by producing less drilling waste and lighter equipment take less space. Potential benefit of the method include also: less requirement on crew and reduced human hazards by automated equipment, RIH/POOH is quicker because no connection is needed. The ability of the remote control and real time transmission is being improved by adapting cable on coiled tubing **[11].**

In 1993, 5 oil contractors and 6 service companies participated in to study the concept of slim hole coiled tubing drilling by analysis of application in deep well. Their study concluded that the slim hole reduced the cost dramatically resulting from reduced material. Furthermore, the drilling mud for 300 m is estimated to be only 0.16 m^3 with slim hole drilling compared to the traditional drilling which is ten times of that **[11].**

The research for slim hole coiled tubing concluded also that it is not only lowering the cost but has also the capability to reduce the hazard on environment. It is promising technology which the oil industry needs to put more and more emphasis to improve and make new researches in order to achieve or even exceed international standards. The author indicated also that the study of basic subject in this technology is big effort to accomplish its development. Another big aspect to improve this technology is also introducing more experience from countries such as Canada and USA where coiled tubing technology is more mature **[11].**

2.3.2 Continuous coring technique

Slim hole drilling with continuous coring method provides the potential to obtain large quantities of geological information from core samples. This technique is used on the mining industry to certify that an ore body discovery contains a sufficient mineralogical grade in order to justify full-scale mining. This is usually lead to coring of up to 90 percent of a well **[7].** Oil and gas industry adapted the technique for exploration drilling in the late 1950s. However, the effort to consider slim coring began in 1980s and 1990s with companies such as Strato Drill Inc. in Texas USA **[7].**

The technique offers the potential to deliver the core facilitate rate of penetration (ROP) and maintain minimum pressures on the formations penetrated. An oil-emulsion type inhibited is commonly used to prevent hydration of shales and solution of salts. Hence, a formation of high pressure is penetrated which could cause a catastrophic situation such as a blow out or fracture of shallow formation. Therefore, a pressure gauge is located inside the drillers view that indicates the pressure in the hole annulus. Due to the fluid being static in the hole annulus, the pressure is obtainable. In addition, a heavy standby mud is maintained of high lubrication and low water loss characteristics to prevent blow out and treat lost circulation.

This method was designed to provide a large detailed reliable subsurface information at the time of penetration and at time of greatest need. Using this technique, Strato Drill Inc. Tested over wide variety of formation in well in Texas, USA providing 100 percent of the core of the sections penetrated. Although a good recovery rates have been stated, the technique is more than satisfactory in rate of penetration and evidenced side advantages such as minimized lost circulation, no caving , bridging, accurate WOB control, a smaller rig sizes are used and better hole condition for testing and completion than traditional method.

A slim hole test was made to analyze the cost of required hydraulic pressure, pump volume, Pump horse power (HP), mud and drill site. **Table 2.2** summarize the comparison of hydraulic requirement of the core drill technique and conventional drilling. The basis of the test data include: **[12]**

Hole size: 7 inch (17.78 cm)
Ascending mud circulation velocity: 3 ft./s
Mud: 9.5 ppg
Viscosity of mud: 3 cP
Conventional drill pipe OD: 3 ½ in API
Core drill pipe OD: 4 Inch and 2 ½ in core tube

Table 2.2: Comparison of hydraulic requirement of the Core Drill vs standard drilling [12]

		FRICTION LOSS	FRICTION LOSS	TOTAL	FRICTION HP
DRILL, Ft	Mud Vol	Per 1000 ft.	Per 1000 ft.	Friction	per 1000
	Gal/min	descending	ascending	loss/1000	
Conventional	270	14	13	153	34,5
Core Drill	37	17,5	11	28,5	0,86
RATIO:					
Conventional	7,3	8	1,1	5,4	40
Core Drill	1	1	1	1	1

The tests conducted of continuous core technique has been concluded as viable tool for oil and gas exploration as it obtains 100 percent core recovery and allows detailed evaluation of formation penetrated. Hence, it provides higher drilling efficiency and reduced cost by continuous determination of optimum WOB and optimum rotary speed. The technique also offers less labor requirement, less mud volume, reduced chance of lost circulation, no need for logging and better condition hole for completion **[12]**.

One of the most benefit of the continuous coring method is the utilization of small modified mining capable of continuous coring using wireline retrievable core barrels that has the ability to maintain high rate of penetration and still offer high recovery rate while coring compared to the conventional coring method. Because of the ability to retrieve the core without tripping the pipe. The significantly reduced rig size results to reducing site costs when drilling in remote exploration location **[12]**.

The technique is a great step forward in the development for better drilling method but the problem associated around drill string and hydraulics can be sceptical to the oil and gas companies. Because of the smaller annulus that maximizes the hydraulics, fluids which could result in well control problem. The technique has a thin wall pipe that does not allow sufficient WOB to be applied and bottom-hole assemblies for weight. The limitation of the depth which is about 3000 meter can be another big issue for the petroleum industry to imply this method **[13]**.

The current efforts by the companies viewed of this drilling technique by investigating the potential of slim-hole continuous coring. As result of their study, it has been found a minor and major alteration for the use of mining rigs in specific project. Therefore, the use of continuous coring only the lower true slim-hole sections is preferably considerable while performing more conventional drilling in the upper part **[13]**.

2.4. Types of Slim hole Wells and Their Applications

2.4.1. Slim hole technology for exploration in remote area

Slimhole wells may very beneficial in remote exploratory areas. Such areas are where both the risks and potential for rewards are increasing because of lack infrastructure or an established company presence, the road construction and logistics can be expensive. In this situation, introducing the concept of drilling small diameter wells may become attractive**.** The method can be more efficient in such areas by using smaller rigs and equipment where it can easily be transported by a helicopter or along with the existing road with no need of upgrading **[14]**.

Such wells use less mud, casing, cement, water, diesel and they generate smaller volume of cuttings and require less people to operate and support the drilling system. The environmental impact in exploration and production also plays a significant role as slimhole to become ‘’smart’’ holes. As shown in **Figure 2.4,** the size of the well site reduced by 75 percent, mud consumption and cuttings reduced by 75% , and the hole diameter reduced by 50%. The overall cost reduced from 40 % to 60% compared to Conventional Well **[14]**.

In 1990, BP Exploration (BPX) identified the potential benefits of the slim hole exploration in screening its remote properties. It is been conducted field research lead by BP research to investigate the strength and weakness of the slimhole drilling **[14]**. BPX drilled six wells for evaluation program on it onshore Plunger Field, England. BP recorded 70 % savings in site preparation than a conventional rig. The time savings on rigging up and down the smaller equipment reduced transportation cost by 60% to 70%. In one application, the smaller hole size in Sixfold recorded decrease in formation cuttings volume and resulting reduction in disposal cost. It is been achieved a savings resulting from a reduction in consumables such as rock bits, muds, cement and fuel oil **[7].** They concluded their study that a cost savings in excess of 40% were achieved in the slimhole exploration project.

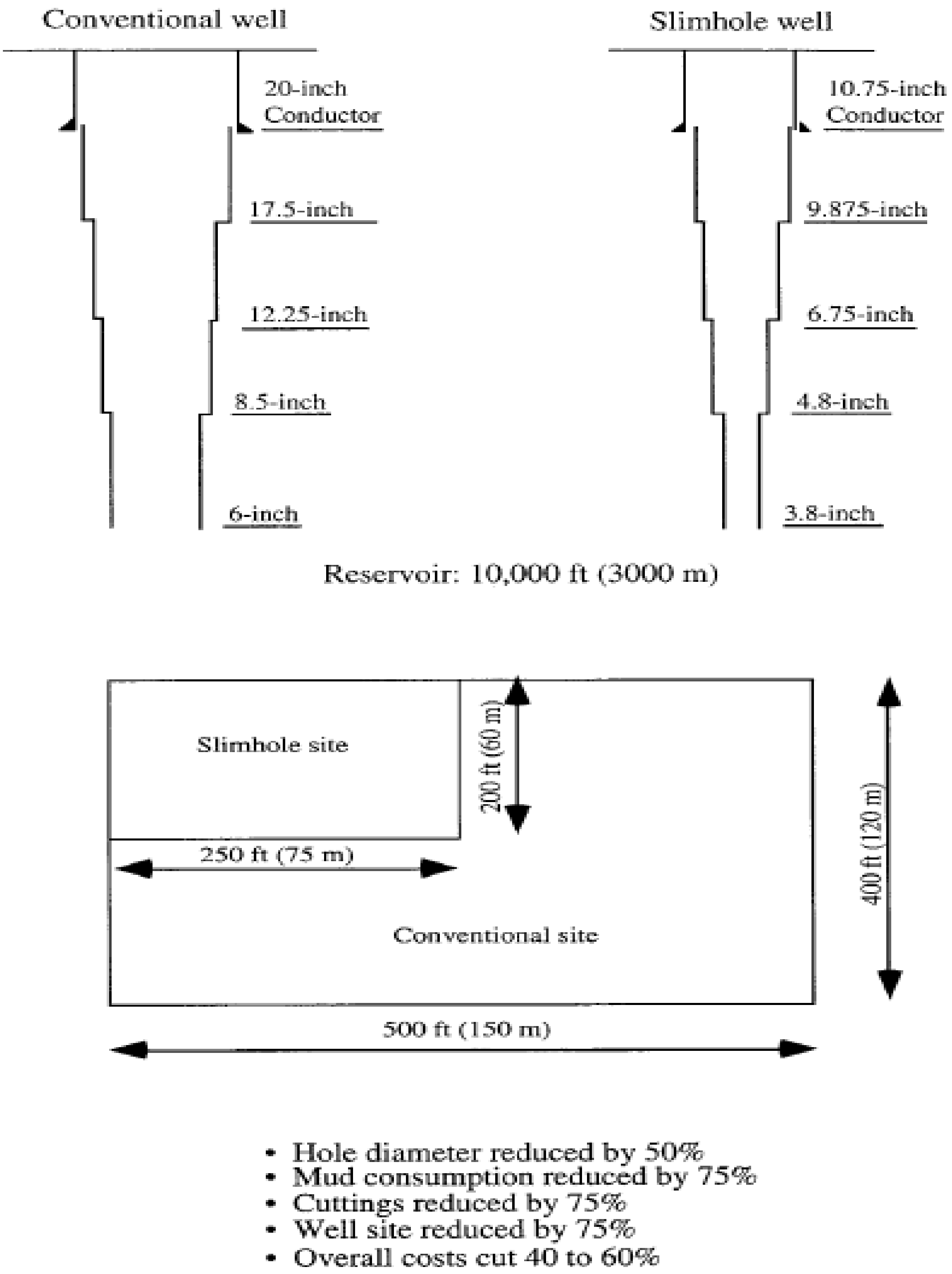

Figure 2.3: *Slimhole Technique reduces both Well and Site Costs [6].*

2.4.2. Slimhole Technology for Horizontal Drilling

A recent trend that certainly operators will be adapted over the next few years is the need to drill what is called `` Slim hole horizontal’’. Because of the use of slim hole horizontal that can be drilled at successively smaller diameter wellbore to reduce costs has been made possible to replace the need for larger wellbores to handle the high flowrates. Even though the principle benefit of the smaller diameters of slim hole is a reduced cost, but in practical applications proved that the method could limit the potential ability of the well to produce, and other factors such as low rock permeability can also be a limiting factor. However, not productivity but reduced cost can be deciding factor in the horizontal lateral length and diameter. For instance, a such areas where is desired to intersect a large number of fracture to improve production but the well is not sufficient productive and reserves are not enough to pay for the additional costs of a larger lateral hole, a slimhole completion can be an efficient method. Due to its principal benefit: reduced cost, operators are willing to take the greater risk and limitation associated with slimhole horizontal well **[6]**.

In late 1991, Oryx energy Company developed the concept a slimhole horizontal drilling program in Pearsall Field located in South Texas. It was decided to develop an extensive horizontal drilling program to drill new wells in this area. In **Fig.** 2.4.2 shows a typical drilled well in the fractured Austin Chalk formation. The idea was to reduce costs in such areas where productive rates were not contingent on the size of the lateral wellbore. Because the use of smaller drilling rigs or workover rigs and smaller casing size can minimize drilling cost in horizontal wells. Three wells were drilled to evaluate the proposal using a smaller drilling rig to the intermediate casing point. The intermediate casing was run and cemented. The drilling rig was released, then the workover rig replaced to drill the curve and lateral section. This offered to two benefits. The first one was a small drilling rigs could drill the upper hole more rapidly than the workover rig and at reduced cost than that required to drill conventional wells. Secondly, the less expensive workover rig could more easily manipulate the tubing used for the drill string **[13]**.

Results from Oryx seen in slimhole horizontal drilling operation showed a significant cost reduction. Based on the results of the second well that performed under very typical conditions seen in drilling operation in the Pearsall Field. It has been found complete lost circulation, it drilled while the well was flowing, and drilled through unconsolidated volcanic as intervals with little problems. Even though the hourly penetration rates were the equivalent of those seen in larger conventional wellbores, the costs were significantly reduced. The cost of this slimhole horizontal wells from first well is reduced 20% while savings nearly 32% of conventional design and 16% from the reduced hole design were also seen. The following table shows the comparative drilling cost for newly drilled wells.

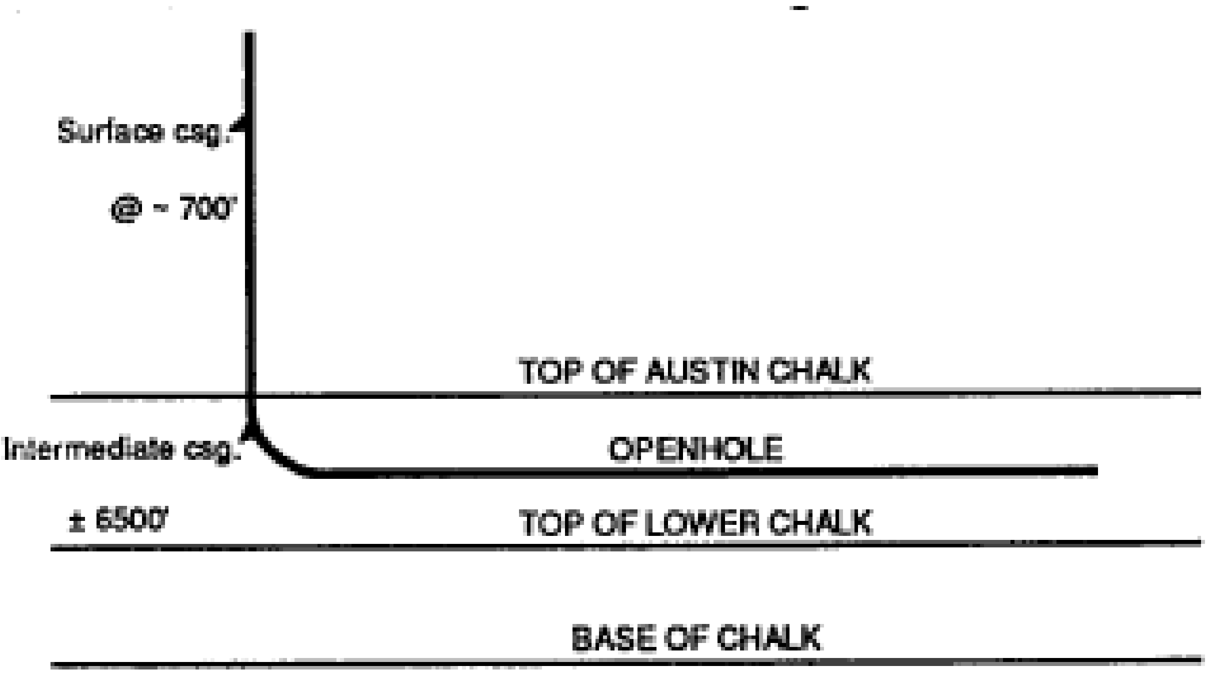

Figure 2.4: *Typical newly drill wellbore configuration in Austin Chalk formation [4]*

Table 2.3: *Comparison for the newly drilled wells in terms of drilling cost [4]*

	Hole Size	**Depth/ Displacement**	**Total/ Cost index**	**Lateral Cost Index**
Conventional	8 ½ ‘’	10389’/3741’	1.00	1.00
Reduced Hole	6 1/8’’	9,698’/3,257’	0.84	0.87
Slimhole	4 ¾ ‘’	9,697’/3,154	0.68	0.73

Cost index refers to total well costs while Lateral cost index is the cost associated with lateral hole.

The results from these wells show that slim hole horizontal drilling operation, whether re-entry or newly drilled wells provides significant potential for cost savings and were promising. Based on the results, the technology shows a great promise and must continue to do so to meet the needs of the petroleum industry. In table 2.4.3 shows the actual cost beneficial that were seen from the use of slim hole operations in Oryx’s Pearsall Field operations.

Table 2.4: Performance comparison Drilling Cost Slim hole vs Larger design [4]

INDEX	HOLE SIZE	DEPTH/DISPLACEMT	TOTAL INDEX	LATERAL COST
Conventional	8 1/2"	10,289/3741	1	1
Reduced Hole	6 1/8"	9,698'/3,257"	0,82	0,87
Slim hole Re-entry	3 7/8"	……../1980	0,5	2,38
Slim hole New Well	4 3/4"	9697/3154	0,68	0,75

2.4.4 Slim technology for Re-entering Existing Wells

The use of slim hole drilling to re-enter wells are into two ways: sidetracking existing wells to horizontal or deepening existing wells. In this technique of sidetracking, a portion of the existing casing is milled out by either applying section milling or window milling operations. Then the hole is sidetracked to horizontal. Window milling operation does not need a cement plug for kicking off and less casing is removed compared to section milling. In this case, the sidetracking is achieved while cutting out the window. Therefore, window-milling operation can reduce the time required for sidetracks **[6]**.

In 1990, Oryx drilled a number of re-entry horizontal slim hole wells due to the need to utilize existing wells in marginally productive area of the Pearsall Field. It was planned to mill a section in the production casing and kick off out of the section. This was to achieve 2000-2500 ft. of departure. It was planned to drill a 4-1/2 inch lateral even though the wells had 5-1/2. All the work was done continuous operation (24hr) workover rig. Although five wells were re-entered, the result was not convincing in terms of cost. Lateral hole costs were higher on a per foot comparison. In this case, the program was terminated. However, in 1991, interests was renewed in looking re-entries for evaluating these marginal areas. There was some improvements by the equipment and techniques used previously. Hence, technology to utilize coiled tubing in order to serve as the drilling rig was developed. Due to increase of the daily ROP by 55% and lateral displacement by 6%, the results were economically encouraging. This also reduced the number of day by 31%. In addition, the increase of ROP and reduced problems resulted 53% well cost reduction. A significant cost reduction was achieved in that conventional drilling costs had been reduced by 21% through improved operations and the conventional hole lateral costs had been reduced a dramatic 67% from the previous year.

Baker Huges and Husky Oil Operation (Hollies and Szutiak, 1997) reported the successful application of slim-hole drilling techniques to revive the drilling problem for re-entry well in the Rainbow Lake Field. The horizontal section had drilling problems such as differential sticking, lost circulation, an overlying gas cap and sour uphole zones in the build section. In the slim hole approach, intermediate liner (4 ½ inch) was run into the curve, then the lateral is drilled with a reliable 3 -7/8 inch slim hole system. According to husky, the completion of these wells resulted no more expensive than the conventional single- size version. Even the production rates were similar for slimhole and conventional. The savings with the slim-hole dual size section become 10-15% less than conventional. In addition, it has been also compared the productive time and cost for conventional re-entries and the slim-hole dual hole. The last one was the most efficient in time and cost. After learning the experience from the slim-hole completion, it showed a dramatic reduction in cost with time and the length of lateral has also increased significantly. Husky found that slim-hole performance has been consistent as the technique have been improved as well as the well cost per meter of horizontal hole has improved $ 203/m making 28% improvements comparing to a new grassroots horizontal. Hence, the slim-hole re-entries operation can be successfully completed on an average of 17 days **[15]**.

BP Exploration Inc. drilled 50 sidetrack wells by drilling new wellbores from low yield or damaged wells. The company reported that sidetracking technique minimized the drilling cost up to 55% thus from $ 2.2 to $ 1 million for marginal areas of the Prudhoe Bay reservoir. In addition, sidetracking also improved the reserve for the Prudhoe Bay reservoirs. For instance, one horizontal sidetrack that has been drilled into Ivishak field’s zone one is producing up to BOPD from previously unproductive well. Because of the horizontal sidetracking allows to access those thin, segregated layers of oil that earlier was uneconomic to produce.

In another company, Union Pacific Resources Co. (UPRC) reported that the average drilling cost for performing a reentry horizontal well in Pearsall Field, was up to $100/ft of exposed formation comparing to an average $162/ft for a new horizontal well in the same area, the benefit ranged up to 38%. The Fig.2 provide the cost savings for different types of re-entries.

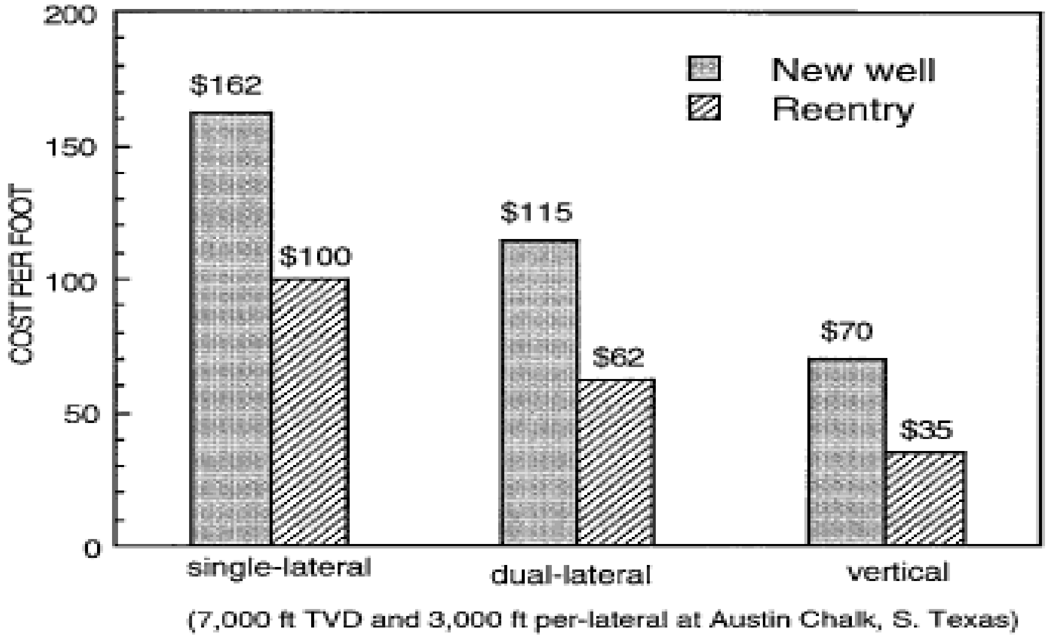

Figure 2.5: *Cost Reduction for Different Types of Re-entries [6]*

2.5 Benefits of Slimhole Drilling.

2.5.1 Reduction for Drilling Cost

The use of slim hole technique offers significant economic advantage over conventional practice by reducing the drilling cost. The slim hole results are reported to be proving effective. With the current condition in oil industry, the cost savings is very important aspect because of the reduced capital investment. Slim hole exploration project in remote location reported 30-60% cost reduction and 25-40% for development wells less than conventional drilling operation **[16]**.The saving can be achieved in variety of categories including:**[4]**

- The use of smaller drilling rigs and/or workover rigs
- Reduced casing sizes
- Less site preparation and easier mobilization of equipment
- Less capital investment
- Minimized drilling waste and other costs associated with hole size
- Less cuttings volume, rig rate and time, cementing, mud and fuel costs.
- The less cutting volume allow more efficient mud cleaning or use of cheaper solids formate brine.
- Easier to be able to drill, evaluate and complete through the reduced casing sizes.

The composite experience of the Carter Oil Co revealed a significant savings of $ 162,000 in slim hole drilling practices. In terms of bit life and penetration rate, slim hole drilling performance showed bit to 82% of conventional value and required 35 rotating hours on bottom while conventional experience ranged from 33-62 hours. Overall slim hole savings evolve from reduced footage rates and reduction in day work, volumetric reductions and improved rig mobility. In this case, slim hole wells indicate a significant economic advantage over conventional drilling if properly sized slim hole equipment is used **[3].**

2.5.2 Minimization of disposal cost

During drilling operation, it is important to consider the amount of cuttings volume, mud volume, cement and completion fluid that have to be disposed of. With current increasing costs associated with waste disposal, the oil industry are seeking new technology that pollutes less, and smaller hole sizes that requires less mud, cuttings and cement. One way to achieve this is by reducing the hole size drilled to less than what is typically drilled in conventional oil well. For instance, a slim well with a hole size that is half of a conventional one enables to reduce the cuttings volume to around 25% of conventional volume. This will greatly lower costs of waste disposal. According to Floyd, the smaller diameter wells of sixfold was recorded decrease in formation cutting volume and a corresponding reduction in mud volumes. Generally, the annular volume of slim hole wells is an orderly magnitude smaller than conventional annular volume **[7]**.

2.5.3 Technical and Environmental impact advantages

As the environment is becoming something that is focused more and more upon, reducing the environmental impact of drilling becomes more of a priority for the oil companies. Therefore, slim hole drilling can be the new technology that reduces the environmental impact and contributes to reduce such as noise levels, exhaust emission and disposal wastes. This aspect is already important as the environment becomes more and more crucial for drilling wells in the future. Therefore, the industry have to change its habits and consider this environmental aspect with care and has to anticipate the future needs of regional, international laws which will be rapidly implemented. However, slim hole technology provides the opportunity to minimize waste, this can be seen for the following factors; **[17]**

- Reduction of access road, track, and the site derive from the rig components weights and sizes.
- The location size 1000 sq (10 000 sq ft) that is 6 time less than a normal site

- Drilling wastes volumes are divided by 3, which allow an easy physic treatment, and in the future a stabilization and solidification on site.

Using small equipment in slim hole drilling makes particularly suitable for sites demanding a low impact on the environment. The compactness of slim hole drilling rig has environmental benefits such as the drill site area can be significantly reduced. Slimhole drilling rig is capable using drill site location less than 7500 ft^3 while conventional drilling rig requires at least four times the areas as shown in **Table 2.5**. the drillstring weight, mud tank and rig weight for slim hole drilling at total depth of 5000 ft are much less than conventional drilling. As can seen on table, the power required to pump the mud for slim hole drilling is also less than to that conventional, thereby reducing fuel consumption and air pollution. Using slim rig will also reduce the noise. This is particularly beneficial when drilling near residential location **[7].**

Table 2.5: *Comparison of Conventional and Slimhole Rigs at TD 5000ft*

Type of Rig	**Conventional**	**Slimhole**
Hole Diameter-in	8,5	3 to 4
Drillstring weight, Metric tons	40	5 to 7
Rig weight, Metric tons	65	12
Drillsite area, %	100	25
Installed power, Kw	350	75 to 100
Mud pump power, Kw	300	45 to 90
Mud tank capacity, bbl	470	30
Hole volume, bbl/100ft	60	6 to 12

2.6 Limitation and Potential Disadvantages

From technical and economic standpoint slimhole drilling promises to cut the drilling and completion costs significantly. It may also offer significant potential to reduce workover costs. However, the savings achieved by the cost reduction from slimhole drilling can be offset by increased mechanical failures, reduced lateral hole length and lack of directional control **[4**]. From the standpoint of the oil industry, the adaptation of slim exploration wells brings new challenges to the oil fields:**[18]**

- Formation testing in small- diameter wells needs to be considered and studied.
- New technology is needed to improve some of the problems and limitation of slimhole drilling and improve real-time analysis of cores and logs

- Cementing operation might become difficult with respect to channeling behind pipe and fracturing of weak formations due to the high pump pressure required to overcome the increased friction in the small annulus.
- Kick detection is a difficult issue because the annulus contains such a small fluid, a kick poses serious threat of emptying the well. As result of the small annular clearance, most of the pressure drop occurs in the annulus section.in contrast, those wells drilled with conventional drilling rig, the pressure drop occurs in the pipe. Therefore, kicks must be detected early after only small influx of fluid.
- Safety of the rig and crew presents additional problems in areas including kick control and early gas detection.

In addition, depth can be a key limiting factor when designing a slim well. However, many of the advances in technology now enable to reach to 17000 ft. Chevron recently reported a slim hole well design at increasing depth to around 17000ft in the Carter Creek field in Southwest Wyoming **[19]**.

Some of the disadvantages with drilling slim wells can be- high ECD that can limit mud weight, limit completion options, production rates and potential for future sidetrack options, limited amount of raw petrophysical information obtained.

3 THEORY

This chapter presents theories used to evaluate the performance of slim hole technology. These are drill string mechanic, hydraulics and hole cleaning. Uses these theories, simulation studies will be presented in chapter 4 and 5.

3.1 Introduction

The literature review in previous chapter has shown that slimhole drilling can be offset by mechanical failures. These issues can affect operations, economics and can also pose significant challenges for the operator. Therefore, the technologies such as WellPlan Landmark that have been found can be vital to the success of slimhole drilling. These include:

- Torque, drag and stresses in drillstring
- Hydraulics and Hole cleaning
- Equivalent Circulation Density
- Others, well design, drillstring design

To ascertain a background for the simulation study in chapter 4 and 5, a basic theory with view to understanding the science and technology behind torque, drag, stresses , hydraulics and hole cleaning will be reviewed in the following sections.

3.2 Torque and Drag

In this section, the theory for Torque and Drag will be presented, as well as the buckling and tensile limit. The purpose of the theory is to provide us the fundamental for understanding using mechanics of materials to design safe operational window (buckling and tensile limits, Drag and Torque, stress in the drill string). Before proceeding with various simulation study through WellPlan, the basic principal for T & D model are defined.

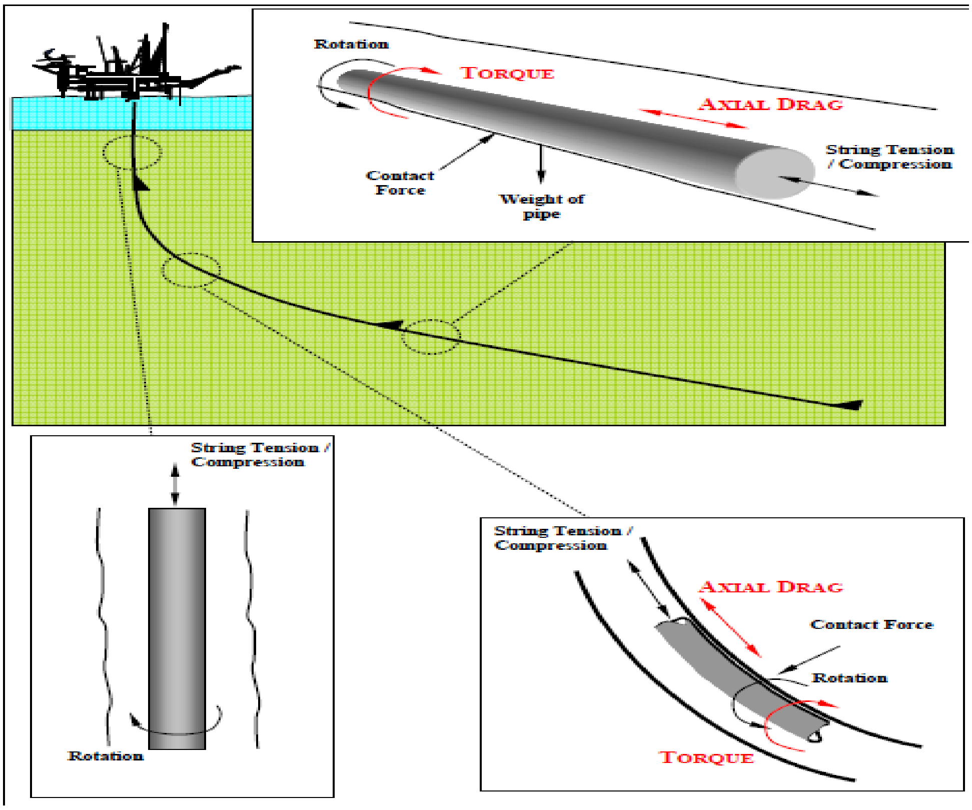

Figure 3.1: Drill string forces in the borehole [21]

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3.2.1 Drag in Inclined Well

Drag is the additional load compared to free rotating drillstring weight. This additional load is usually positive when tripping out of hole and negative when tripping into hole. The drag force is mainly generated by the drillstring contact with the wellbore due to friction.

From force balance, applying the condition of equilibrium along the axial directions, force balance along the inclined plane one can obtain: **[20]**

$$dF = w\Delta s(\cos\alpha \pm \mu \sin\alpha) \tag{3.1}$$

Where the plus and minus sign allows us for the load movement direction whether pulling out of the hole or running in to the hole.

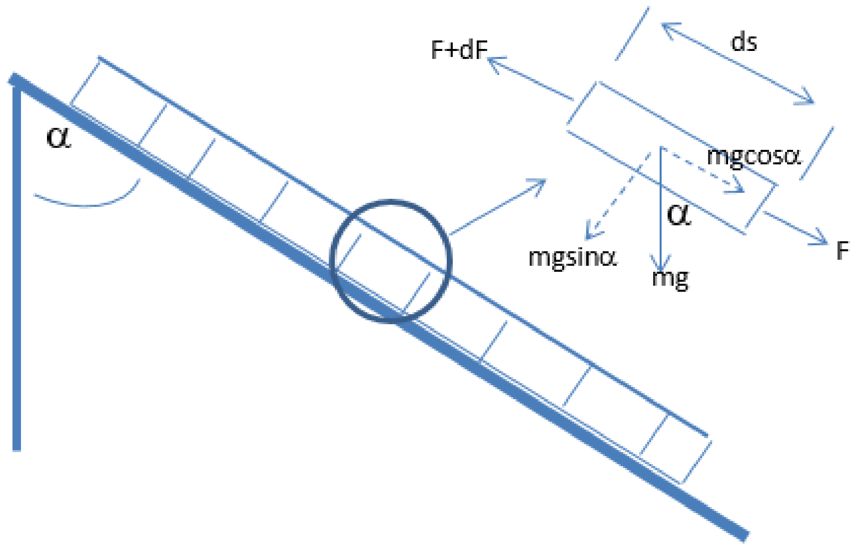

Figure 3.2: Forces acting on inclined Drill string [20]

Johancsik assumed both Torque and Drag assumed to be caused that result from contact of the drilling string with the wellbore by sliding friction forces. He then define the sliding friction force to be a function of the normal contact force and the coefficient of the friction between the contact surfaces based on the coulomb's friction [**22**].

Based on coulomb friction model, an increase or decrease in the load will lead to downward or upward movement when the drill string is stationary. Integrating the equation stated above over the top and bottom load limits, one can present the force in the drill string as: **[20]**

$$F_{top} = F_{bottom} + w\nabla s(\cos\alpha \pm \sin\alpha) \tag{3.2}$$

The "+" means pulling out of the hole while $\ll - \gg$ defines the running into the hole. The first term inside the bracket defines the weight of the pipe and second term defines the additional friction force required the pipe. The change in force when the motion acts upon either upward or downward is found by subtracting the weight from the forces stated above. The static weight is given as:

$$w\nabla s\cos\alpha \tag{3.3}$$

The torque and rotating friction follows up the same principle. The applied torque is obtained by multiplying the friction factor μ with normal moment($w\nabla sr$), giving torque as: **[20]**

$$T = \mu w\nabla sr \sin\alpha \tag{3.4}$$

3.2.2 Drag in any curved well

The following figure show represents a drill string which is divided into segments. These segments are loaded at top and the bottom with compressive $(-)$ and tensile $(+)$ loads. Furthermore, these loads, thermal, hydrostatic and fluid flow shear forces are also responsible for the length of the drill pipe.

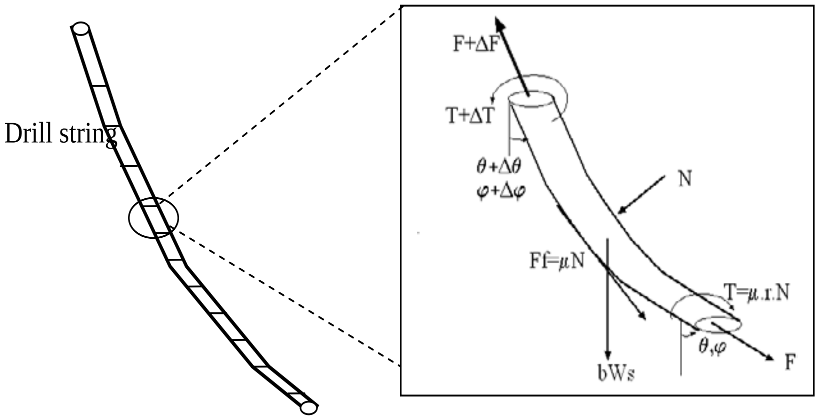

Figure 3.3*: Segmented Drill strings and loadings[20]*

Balancing between the net force and the vector sum of the axial component of the weight, W and the friction force, first order differential force can be found as the following (Johansick):**[24]**

$$\frac{dF}{dS} = \pm\left(\sqrt{\left(\beta w_s \sin\theta + F\frac{d\theta}{ds}\right)^2 + \left(F\frac{d\theta}{ds}\right)^2}\right) + \beta w_s \cos\theta \tag{3.5}$$

Where the plus and minus sign consents for pipe movement direction, ‘’+’’ is when pulling out of the hole (hoisting) where the friction adds to the axial load and ‘’-‘’ is running into the hole (lowering), in other word downward motion, the opposite.

The equation above, square root term indicates the normal force per unit length for any curved well geometry. The equation is function of well inclination(θ) and azimuth(α), where each segment can be calculated as the following:'

$$N_i = \sqrt{\left(\beta w_i \sin\left(\frac{\theta_{i+1}+\theta_i}{2}\right) + F_i\left(\frac{\theta_{i+1}-\theta_i}{S_{i+1}-S_i}\right)\right)^2 + \left(F_i \sin\left(\frac{\theta_{i+1}+\theta_i}{2}\right)\left(\frac{\alpha_{i+1}-\alpha_i}{S_{i+1}-S_i}\right)\right)^2} \tag{3.6}$$

Where: w_i =weight per unit length
β = Buoyance factor

Buoyancy effect

Buoyance is actually a design parameter and has a very important effect in deep petroleum wells. It plays an important role that the unit mass of the drill pipe or the weight is corrected by buoyancy. The standard buoyance factor is given as: **[24]**

$$\beta = \frac{Suspended\ weight\ in\ mud}{Weight\ in\ air} = 1 - \frac{\rho_{mud}}{\rho_{pipe}} \tag{3.7}$$

The above equation is valid if the inside and the outside of the pipe are filled with mud. An equation where different density exists on the inside and outside of the drillpipe. The following equation results**: [20]**

$$\beta = 1 - \frac{\rho_o ro^2 - \rho_i ri^2}{\rho_{pipe}(ro^2 - ri^2)} \tag{3.8}$$

The above equations are both valid for vertical and deviated wells, and the buoyed unit must be:

$$w = \beta w_{drillpipe} \tag{3.9}$$

3.2.3 Torque

Torque or moment is rotational force and generally defined as a result of force multiplied by an arm. It is the moment required to rotate the pipe and the rotational force should overcome the frictional in the well and on the bit with the formation during drilling. Torque is mathematically expressed as:

Torque= Force x Distance

High torque and high drag forces are normally associated with each other. In drilling application, an ideal vertical well the torque loss would be zero, except for a small loss due to viscous force resulted by mud. However, if is in a deviated well the torque loss may be significant, especially in long complex or extended reach well. In drilling operation, torque loss is a major limiting factor to how long drilling can be continued. Torque is dependent to the radius of which rotation occurs and the friction coefficient and the normal force over pipe.
The increment torque calculation is: **[20]**

$$\Delta T = \mu N_i r \Delta S \qquad (3.10)$$

In conditions when both buckled and non-buckled string the torque loss per unit length is represented as

$$T_{i+1} = T_i + \sum_{i-1}^{n} \mu r_i \, N_i (S_{i+1} - S_i) \qquad (3.11)$$

3.2.4 Friction factor

Friction Factor also known as friction coefficient plays an important role in drilling operations and in the solid mechanics calculations due to torque and drag as well as hydraulic calculations, including surge, swab and hookload estimation during cementing. One of the challenges during drilling, running casing and completion is to minimize torque, drag and stress in drillstrings. As we drill deeper or inclined wells, friction increases because of the increased contact area between the drillstring and the wellbore wall. Therefore, the friction force must be considered when the workstring is tripped out/in or rotated on/ off bottom. The simulation of drilling operation with the friction force is very complex due to some uncertainties that affect the friction term **[25].**

Friction factor is not really pure friction factor at all but more of a “fudge factor”. Because there are several issues to be considered in addition to friction. They include**: [21**]

- Mud system lubricity
- Hole cleaning (Cuttings bed)
- Pipe stiffness and key seats
- Dogleg severity and wellbore tortuosity
- Stabilizer and centralizer interaction
- Consideration to the type of operation (e.g. rotating or sliding)

Furthermore, it should be noted that Slack-off, pick-up and torque friction factors might appear to be same in the nature but in reality, they are different. The industry will usually only allow a single friction factor for a given hole section. For instance, in our simulation study it is essential at the beginning of the project to establish a database for cased hole and open hole friction factors for the mud type used. However, In order to model torque and drag accurately, it is important to note that separate friction factors are required for pick-up, slack-off and torque. Table 3.1 shows the typical coefficient of friction to different types of fluid **[21].**

Table 3.1: *Range of friction factors [25]*

Fluid type	**Friction Factors**	
	Cased Hole	Open Hole
Oil-based	0.16-0.20	0.17-0.25
Water-based	0.25-0.35	0.25-0.40
Brine	0.30-0.40	0.30-0.4
Polymer-based	0.15-0.22	0.2-0.30
Synthetic-based	0.12-0.18	0.15-0.25
Foam	0.30-0.40	0.35-0.55
Air	0.35-0.55	0.40-0.60

In most torque and drag analysis models, the friction coefficients are calibrated to enable to adjust the mud weight as well as the string weight and consequently, enables to match the calculated pick up, slack off and torque values to the actual value measured on the rig. The friction factor back calculated for pick-up and slack-off is usually different than one used for the torque. The discrepancy between the friction factors may be due to the type of either soft string or stiff string model used. Some discrepancy may also exist between the pick-up and slack-off friction coefficients. This could be due to the different borehole conditions or due to the compression force in tubulars incorrectly modeled with the type of model used during this operation. Friction coefficients are mainly dependent on mud type and lubricity, open hole and cased hole and contact force. However, the friction coefficient is not depend the tortuosity of the well path since is usually masked behind friction factor that are falsely higher than it should be **[26].**

3.3 Stresses in drill string simulation

Stress is defined as force per unit. In this section, the theory to analyze stress in drill string used in WellPlan software simulation will be presented. The main purposes for stress analysis is to ensure the pipe body can withstand the operational loads and can be run, pull out of the hole and not buckled during operation. It will also be discussed the theory of thermal and pressure induced stresses in circular cylinder that describes the states of stress in drill string.
Generally, circular cylinders are categorized into two types; thin walled, if $t < 1/10.r$ and thick walled, if $t > 1/10.r$. Where t represents the thickness of the cylinder and r is the inner radius of the cylinder.

In order to derive the stress distribution through the wall thickness assuming the stress is generated due to pressure only, one has to combine conditions such as equilibrium equation, compatibility relations, constitutive stress-strain-temperature relation and appropriate boundary condition. Therefore, the following equations can be derived the stress flied across the thickness of the cylinder as: **[27]**

Radial stress

$$\sigma_r = \frac{P_a a^2 - P_b b^2}{b^2 - a^2} - \frac{a^2 b^2}{(b^2 - a^2) r^2}(P_a - P_b) + \sigma_r(\Delta T) \quad (3.12)$$

Hoop stress

$$\sigma_\theta = \frac{P_a a^2 - P_b b^2}{b^2 - a^2} + \frac{a^2 b^2}{(b^2 - a^2) r^2}(P_a - P_b) + \sigma_r(\Delta T) \quad (3.13)$$

Axial stress

In order to define axial stress, first two types of axial forces known as the “real force”, F_a and the “effective force”, F_e also known as the weight must be defined. The real force is the actual force in the pipe wall measured by a strain gauge while the effective is the axial fore when the effects of pressure are ignored. However, the axial force (tension or compression) applied to the pipe leads to the axial stress. When the CT is in tension, the axial force becomes the axial force divided by the cross-sectional area **[27].**

$$\sigma_a = \frac{F_a}{A} + \frac{P_a a^2 - P_b b^2}{b^2 - a^2} + \sigma_r(\Delta T) \quad (3.14)$$

In case pressure is applied to the fluid inside the pipe, the real axial force in the pipe wall is now increased by the internal pressure multiplied by the cross sectional area. This results the effective force and the real force are not the same. Therefore, the relationship between the real and effective force is given as:

$$F_e = F_a + P_a A_a - P_b A_b \quad (3.15)$$

The above equations are used for thick wall cylinder. Because of the most of the drilling pipe are thin walled type. Equations 3.14-3.16 will be approximated for the thin wall cylinder. In figure 3.5 shows the stress distribution across the wall of the cylinder.

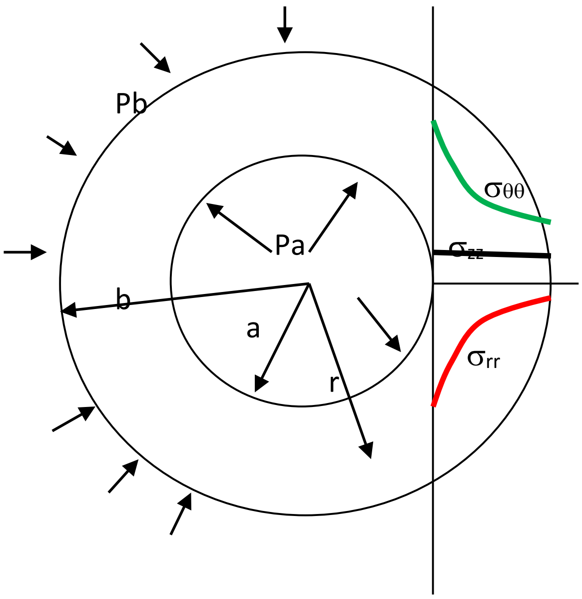

Figure 3.5: *Stress distribution through the wall thickness of the cylinder [27]*

Shear stress

According to Aadnøy (2006), the average shear stress caused by the applied moment is approximated for thin walled wall cylinder. In the presence of torque, T, it can be written as:

$$\tau = \frac{T}{2\pi . r^2 t} \quad (3.16)$$

Bending stress

Bending stress occurs due to the effects of drilling doglegs and by buckling. Both effects are essential and beam theory can be used to find the bending stress. This stress (σ_b) is greater at the outer diameter (D_o) of the pipe. The maximum bending stress can be written as:

$$\sigma_{DL} = \pm \frac{ED}{2R} = \pm \frac{\pi.E.DL.D_0}{432000} \quad (3.17)$$

Where DL indicates dogleg severity given by degree/100ft, R= radius of curvature, + tensile= on the outside of the bend and – compression= inside of the bend. The minimum axial stress can be found as:

$$\sigma_{amax} = \sigma_a - \sigma_{DL} \quad (3.18)$$

While the maximum axial stress becomes:

$$\sigma_{amax} = \sigma_a + \sigma_{DL} \quad (3.19)$$

Then, allowable maximum axial stress that based on zero pressure and zero bending stress becomes:

$$\sigma_{S-SF} = \sigma_{y/SF} \quad (3.20)$$

After converting this equation to force, the maximum allowable axial force is:

$$F_{a-SF} = \sigma_{S-SF} * A \quad (3.21)$$

3.3.1 Failure criteria and designing limit

In this section, Von-Misses failure criteria will be presented because the Wellplan software simulation uses this type of failure model.

The von Mises is based on the combination of three principle stresses (axial, radial and hoop stress) and the shear stress caused by torque. It is commonly used to describe the yielding of steel under combined states of stress. Yielding as function for the combined three stresses is given as: **[27]**

$$\sigma_{VME} = \sqrt{\frac{1}{2}\{(\sigma_\theta - \sigma_r)^2 + (\sigma_r - \sigma_a)^2 + (\sigma_a - \theta)^2\} + 3\tau^2} \quad (3.22)$$

The shear stress term drops out of the equation if there is no torque. In order to calculate the yield limits for pipe one has to set the von Mises stress,σ_{vme} to the yield stress, σ_y for the material.

In addition, the following condition should be considered for designing purpose.

$$\sigma_{vme}^{Design} = max\left|\sigma_{vme}^{Inner}, \sigma_{vme}^{Outer}\right|$$

The tri-axial stress intensity is given as:

$$SF = \frac{\sigma_y}{\sigma_{VME}}$$

3.3.2 Buckling limit

Drill string buckling is a compressive load required to cause drill string failure. During drilling operation, this force is used as limit beyond load should not be applied. There are several buckling loads available in literature.

Among others, which takes the effect of azimuth and inclination is the one derived by [He95]. The model is given as:**[28]**

$$F_{icn} = \sqrt{\frac{\beta N_n EI}{r}} \tag{3.23}$$

Where β is a constant , = 4, for sinusoidal buckling, and 8 + for helical buckling.

For non-buckled string, the normal contact force N = N_n given by

$$N_n = \sqrt{\left(bw_s \sin\theta - F_e \frac{d\theta}{ds}\right)^2 + \left(F_e \sin\theta \frac{d\varphi}{ds}\right)^2} \tag{3.24}$$

Where

$$b = 1 - \frac{A_o\rho_o - A_i\rho_i}{m_e} \tag{3.25}$$

The contact force is not constant. The model presented earlier can be written in the fourth order polynomial equation as [He95]

$$F_{icr}^4 = \left(\frac{\beta EI}{r}\right)^2 \left\{\left(bw_s \sin\theta + F_{icr} a_i\right)^2 + \left(F_{icr} \sin\theta . a_\varphi\right)^2\right\} \tag{3.26}$$

$$a_i = \frac{d\theta}{ds} \text{ and } a_\varphi = \frac{d\varphi}{ds}$$

The above equation can be written in normalized form as:

$$F_{ncr}^4 = \left(1 + a_{ni} F_{ncr}\right)^2 + \left(a_{n\varphi} F_{ncr}\right)^2 \tag{3.27}$$

Where

$$F_{ncr} = \frac{F_{icr}}{F_{scr}} = \sqrt{\frac{r}{\beta EIbmg \sin\theta}} F_{icr}$$

The build rate in normalized form is given as:

$$a_{ni} = \frac{F_{scr} a_i}{bmg \sin\theta} = \sqrt{\frac{\beta EI}{r.b.mg \sin\theta}} a_i \tag{3.28}$$

The azimuth build rate in normalized form is given as:

$$a_{n\varphi} = \frac{F_{scr} a_\varphi}{b.mg} = \sqrt{\frac{\beta EI \sin\theta}{r.b.mg}} a_\varphi \tag{3.29}$$

3.3.3 Tensile limit

Tensile load is a load applied during pulling. The maximum tensile limit is the defined as the load that causes the drill string body reaches to yield point. Using the definition of safety factor, the tensile limit can be calculated by multiplying the yield stress of the material multiplied by the cross-sectional area. The maximum tensile force given as: **[20]**

$$F_y = \frac{A.\sigma_y}{SF} \tag{3.30}$$

Where F_y = Body strength at yield, N σ_y = Yield strength of pipe, N/m^2 A = Crossectional area

3.4 Cuttings transport

3.4.1 Introduction

Efficient removal of cuttings from wellbore is considered as an essential for the success of the overall drilling operation. Insufficient hole cleaning results that the cuttings may deposit and accumulate in the annulus and causes several drilling problems that include: **[29]**

- Increase in drilling string torque and drag
- Poor hole condition can lead to slow rate of penetration
- Stuck pipe
- Difficulty when running and cementing casing (reason for channeling...)**[30]**

To avoid such problems, it is very crucial to handle this situation properly during planning phase in order to achieve sufficient hole cleaning. Failure to remove drilled cuttings can ultimately result such as stuck pipe incidents that can lead to the loss of a well. This only accident may cost over $ 1 million USD which will increase the operational cost for the industry. Moreover, transportation of cuttings in the annulus is very complex process since being affected by many parameters. The major factors affecting transportation of cuttings in the annulus can be categorized into three groups**: [29] [30]**

- ✓ Fluid parameters
- ✓ Cutting parameter and
- ✓ Operational parameters

The drilling fluid has the ability to remove cuttings from the wellbore to prevent deposition and accumulation of cuttings in the annulus. Several factors affecting the carrying capacity of drilling fluid is listed on the following table **[29] [30]**

Table 3.2: *Factors affecting the carrying capacity of drilling fluid*

Fluid Parameters	**Cutting parameter**	**Wellbore configuration + operational parameters**
Mud density	Cutting density	Angle of inclination
Rheology	Cutting size	Pipe rotation
	Shape	Rate of penetration
	Cutting concentration	Eccentricity of the hole
	Bed porosity	Flow rate
	Angle of repose	Depth, hole size/casing well inside diameter

Studies shown that the fluid-flow velocity is the dominant drilling variable on hole cleaning because of its direct relation to shear stress acting on the cutting beds. In horizontal or inclined well, sufficient shear stress should be applied such that the cutting particle are lifted up from the cutting bed surface in order to erode the developed bed. Recently, studies of cutting transport has been in progress. A numerous experimental studies has been conducted and laboratory test results states that in order to remove cuttings for any hole size and hole angle, a high flow rate shows that high flow rate should be applied. However, a higher fluid flow rate may give rise to the equivalent circulation density thus far result well fracturing. In extended reach wells, it is an essential issue to avoid this minimization of pressure loss in the annulus. Because the pressure losses depend on the fluid density, fluid velocity and particle concentration, it is an important issue for the drilling to make compromise between well stability and cutting transport. Therefore, one can optimize an appropriate flow rate for these operations.

Inadequate hole cleaning and cutting transport problems are so common in directional and horizontal drilling. As seen in Figure 3.6, the formation of cutting bed is relatively at higher angles from vertical and also cutting bed would slide down in intermediate angle **[29][30].**

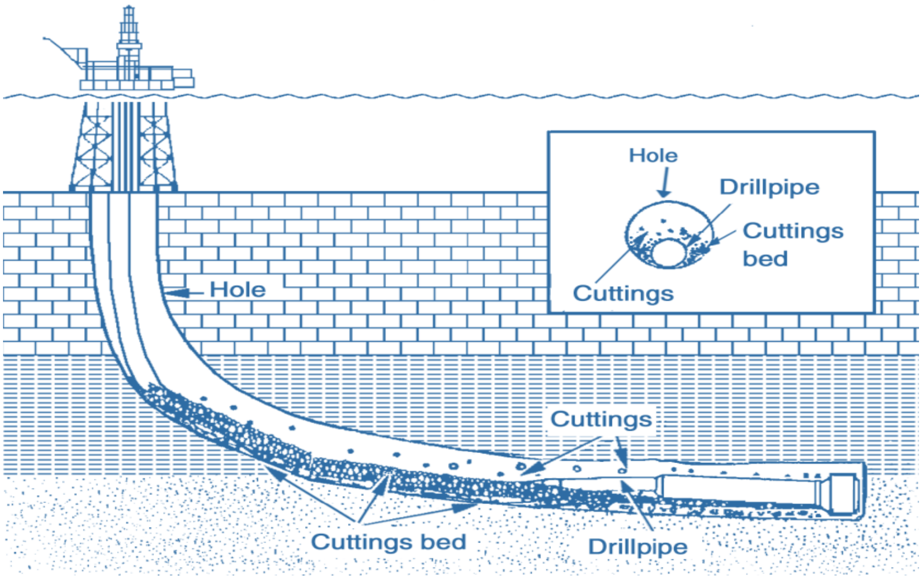

Figure 3.6: Deposition of cuttings in inclined well

Using the same information input data used for torque and drag analysis, in the simulation part, section § 5.2, cutting transport for slim well compared to conventional well. Efficient removal of cuttings from a wellbore is an essential for conducting a successful drilling operation. Therefore, using the Hydraulic module in WELLPLAN software will help to examine the minimum flowrate and determine the minimum flow rate to transport cutting and bed height simulation by using flow rate lower than the minimum allowable flow rate.

The theory of fluid rheology and basic theory related to cuttings transport will be presented in the following sections.

3.4.2 Rheology models and fluid types

3.4.2.1 Fluid rheology

Rheology is the study of the deformation and the flow of fluids. Newtonian model and non-Newtonian model are the two types of rheology model, where the non-Newtonian consists of seven major models (Bingham plastic, Power law, API, Herschel-Buckley, Unified and Robertson stiff). **Figure 3.7** illustrates a typical rheological behavior of the fluid system **[30].**

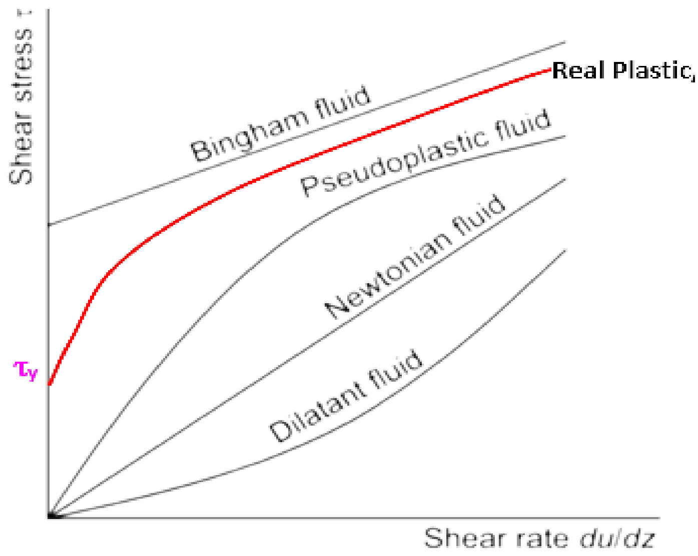

Figure 3.7: *Rheological behavior of the fluid system*

3.4.2.2 Newtonian Fluid

A fluid that obey the newton's law of viscosity are called as Newtonian fluids. An equation of Newtonian fluid is given by

$$\tau = \mu\gamma \tag{3.31}$$

In figure 1, we observe that shear stress (τ) is proportional to the shear rate (γ) as a linear function of a straight line from the origin and the Newtonian viscosity (μ) represents the slope and is dependent of γ.

3.4.2.3 Non-Newtonian fluids

Generally non-Newtonian fluids are complex mixtures which do not obey the Newton's law of viscosity. These include slurries, pastes, gels and polymer solutions.

3.4.2.4 Bingham Plastic Model

Bingham plastic is one of the most widely used rheological model and first two-parameter model. The shear stress –shear rate is directly proportional in excess of the yield stress, τ_Y. The plastic viscosity is the constant of proportionality.

$$\tau = \tau_y + \mu_p y \tag{3.32}$$

However, the model does not represent accurately the behavior of the drilling fluid at very high shear rate (at the bit) or very low shear rates (in the annulus). The yield stress (τ_y) and plastic viscosity (μ_p) can be obtained either by reading from the graph or using the following equation **[30] [31]**

$$\mu_p\ (cP) = R_{600} - R_{300} \tag{3.33}$$

$$\tau_y\ \left(\frac{lbf}{100sqft}\right) = R_{300} - \mu_p \tag{3.34}$$

3.4.2.5 Power Law Model

The power law represents a better behavior of the drilling fluid and describes the fluids without yield stress characterized by non-linear flow curve as given:

$$\tau = Ky^n \tag{3.35}$$

Where the k represents the consistency index and n is the flow behavior index. This popular model with n lower than unity approximates to such fluids after the yield stress is exceeded. These power –law parameters can be obtained from the following equations**: [31]**

$$n = 3.32\log(\frac{R_{600}}{R_{300}}) \tag{3.36}$$

$$K = \frac{R_{300}}{511^n} = \frac{R_{600}}{1022^n} \tag{3.37}$$

3.4.2.6 The Herschel-Buckley (H-B)

The H-B is three parameter model n, k and τ_y that is commonly used to describe the behavior of yield-pseudoplastics.in addition, the H-B model can also represent a shear-thinning or shear thickening behavior depending on the value n **[32].**

$$\tau = \tau_y + kY^n \tag{3.38}$$

The model combines the effects of power-law and Bingham behavior in a fluid **[32]**.

3.4.2.7 Unified rheology model

The model is a modified version of power law model. It is very similar to the Herschel-Buckley model. The Fluids rheological behavior is described with simple equation given by:

$$\tau = \tau_y + K\gamma^n \tag{3.39}$$

Where, the shear stress (τ), the shear yield (τ_y), the shear rate (γ), Consistency index (K) and flow behavior index (n) results from rheometer that used to characterize the fluid behavior (Fann 70 rheology data).

3.4.3 Basic theory related to cuttings transport

Most of the studies have been focused on cutting transport problems. However, a very limited information is available for small sand-sized solids transport which is essential for successful drilling. For any well, it is an important for an efficient hole cleaning. During drilling, all the cuttings are in suspension and when the circulation is stopped, the suspended cuttings may deposit as cuttings bed especially in most high angles and horizontal wells where a solids bed is formed. Since this study simulation is based on two cases of deep wells, a smaller solids are easier to keep in suspension and may easily deposit and form a bed. This can be more difficult to re-suspend since a bed with a smaller particle is more compact than a bed with a larger drilling cuttings, hence more difficult to erode. Field experience and experimental observations showed that inefficient transport of a smaller cuttings causes for excessive torque and drag. Therefore, it is been developed a mechanic model that predict the Critical Re-suspension Velocity (CRV) which is the minimum requirement for hole cleanout when the circulation is stopped **[33].**

The movement of a solid particle in suspension is dominated by the forces acting on the particle as shown in **Figure 4.8**. According to Duan et al **[33],** these loading forces are categorized in three groups: The hydrodynamic forces, static forces and inter-particle forces. According to them, Van der waals forces (F_{van}) are colloidal forces existing between any neighboring particles. Gravity (F_g) and buoyancy (F_b) are the static forces that are due to the properties of the particle and its surrounding fluid. Drag (F_D) and lift (F_L) are hydrodynamic forces incurred from the fluid flow. The forces applied to a protruding particle on a bed depend on the relationship between the solids angle of repose and hole angle **[33].**

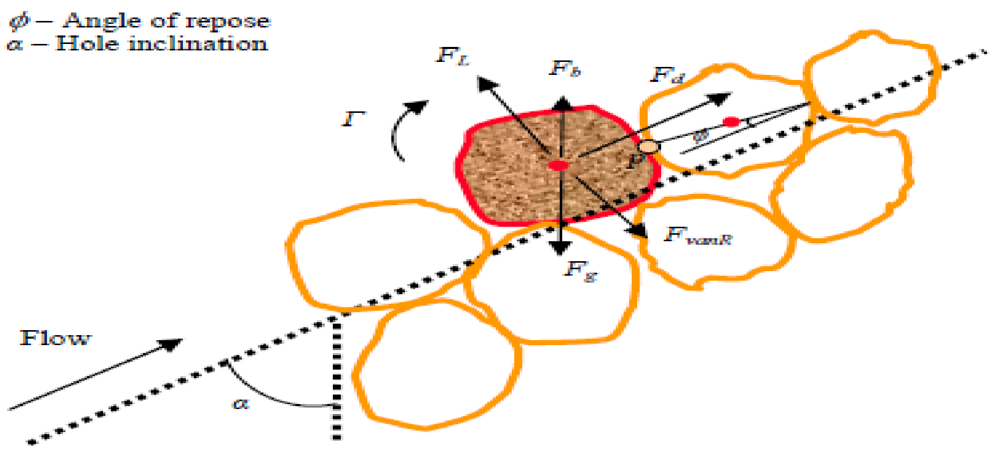

Figure 4.8: *Forces acting on a solids particle on cuttings bed [33]*

3.4.3.1 Cuttings bed properties

The cuttings bed properties have major effects on hole cleaning if the cuttings particles is loose and porous. Therefore, to optimize hole cleaning, it is necessary to remove single cuttings particles that are not adhered to the bed. Some fluid may migrate when the cuttings bed is loose and highly porous and theoretically may reduce the flow above the bed. However, it is desirable to reduce the cuttings bed consolidation as much as possible. In practical operation, it is not expected the migration flow to be significantly large and should not hinder hole cleaning. This means that will be optimized when the bed is as loosely as possible **[34]**.

3.4.3.2 Particle slip velocity

When the particle is in a stationary liquid state, the slip velocity (V_s) can be assumed to equal to the terminal settling velocity. Because of the complex movement of the particle in the annulus, the assumption can be a questionable **[30].**

The cutting slip velocity is defined as the velocity a drilled cuttings have the tendency to fall down through the fluid medium. The fluid annular average velocity (v_a) should be higher than the cuttings average slip velocity (v_s) to be able the fluid to lift the cuttings to the surface. The average cuttings transport velocity is then given by :**[35]**

$$v_t = v_a - v_s \tag{3.40}$$

$$\frac{v_t}{v_a} = 1 - \frac{v_s}{v_a} = R_t \tag{3.41}$$

Where R_t is the cuttings transport ratio

The regime of the flowing fluid and vertical slippage plays an important role when the phenomenon of cuttings transport is considered. If the fluid is under turbulent flow depending on the cuttings shape and dimensions induces a turbulent regime of particle slippage. The momentum forces of the fluid is the only factor that determines the particle slip velocity. The fluid viscosity has little or no influence at all. However, a laminar flow will always provide a lower value of particle slippage. Therefore, the laminar flow will normally provide a better transport than the turbulent flow. If the case is inclined annulus, the benefit of laminar flow will be cancelled while the angle of inclination is increased. Because of the significance of the axial component of particle slip velocity increases **[35]**.

In addition, the terminal velocity of a small particle settling under the laminar flow condition is given by Stoke's laws as: **[35]**

$$V_S = \frac{g d_p^2(\rho_p - \rho_s)}{18\mu_{eff}} \tag{3.42}$$

Where V_S represents slip velocity, d_p= diameter of the particle, It should be noted that, the above equation is only valid for sufficiently small particles Reynold number < 1.

3.5 Hydraulics

Hydraulics plays an important role in many oil field operations such as drilling, completion, workover and production. The two most popular models used for drilling fluid hydraulics are either power law or Bingham plastic rheological model. These models do provide a simple way for fair estimates of hydraulics for conventional vertical well using simple drilling fluids. Therefore, the understanding of the knowledge of rheological data and methods of predicting pressure loss are essential in order to calculate proper pump rate and prevent any barrier in drilling operation **[36]**.However, in this thesis, the unified hydraulic model is used.

3.5.1 Pressure loss due to friction

Drilling conventional wells, the increase in equivalent circulating density (ECD) by annular losses is usually small compared to hydrostatic pressure gradient. According to the standard API RP 59, ECD is defined as the effective density of the circulating fluid in the wellbore resulting from the sum of the hydrostatic pressure imposed by the static pressure and the friction pressure and the mathematical expression of this is given by;

$$ECD = \frac{\sum P_a}{TVD\ .g} + \rho_m \tag{3.43}$$

Where, $\sum P_a$ represents the total annulus pressure loss (Pa), TVD is the hole true vertical depth (m), mud density (kg/m^3), and g- acceleration to gravity (m/s^2).

Because of the narrow annular geometries and thus the smaller the annulus clearance in slim hole drilling, the use of drilling practices is therefore to express this annulus pressure by ECD. The frictional pressure loss depend on several factors including: **[36]**

- Drilling fluid flow behavior of the rheological relation (Newtonian or non-Newtonian)
- The Flow regime of the drilling fluid (laminar, turbulent or intermediate flow)
- Flow rate of the drilling fluid (q)

- Drilling fluid properties such as viscosity and density)
- Hole geometry and Drill string configuration

The drilling fluid is pumped through the surface lines, standpipe hose, Kelly, down the drill string and bottom-hole assembly and circulated back up to the annulus and through the surface mud treating system **[13]**.

During circulation operation when the drilling fluid is pumped, the friction between the drilling fluid and the wall of the drill pipe and annulus results pressure loss: **[37]** the frictional pressure losses mainly comes from:

- In the surface equipment ($\Delta P_{surface}$) such as Kelly, swivel, standpipe.
- Inside the drill string (ΔP_{ds}) and drill collar,ΔP_{dc}.
- Across the bit, ΔP_b.
- In the annulus around the drill string, ΔP_a.

The pump pressure is the sum of the pressure loses and can be calculated as the following equation;

$$\Delta P_{pump} = \Delta P_{surface} + \Delta P_{loss}^{dp} + P_{loss}^{dc} + P_{loss}^{bit} + P_{loss}^{annulus}$$

The frictional losses across the bit is given by;

$$\Delta P_{Bit} = \frac{156pq^2}{\left({D_{N1}}^2 + {D_{N2}}^2 + {D_{N3}}^2\right)^2} \tag{3.44}$$

Where ΔP_{pump} represents the pump pressure. As the velocity of the mud is increased, the pressure loss will increase. The pressure loss will also be higher with decreasing flow area.

Since the friction between the drilling fluid and the wall of the annulus causes pressure loss, the bottom hole pressures will increase when the mud is being circulated compared to when is not circulated. This bottomhole pressure is caused by the hydrostatic pressure of the wellbore fluid and may be calculated in static with the equation: **[38]**

$$P_{BHP} = \rho_{MW} \times g \times D_{TVD} x 10^{-5}$$

In this equation P_{BHP} is the bottomhole pressure given in bars, ρ_{MW} is the mud density in (kg/m^3), D_{TVD} is the true vertical depth of the well given in meters.

In **figure 3.9** illustrates the pressure loss across different sections.

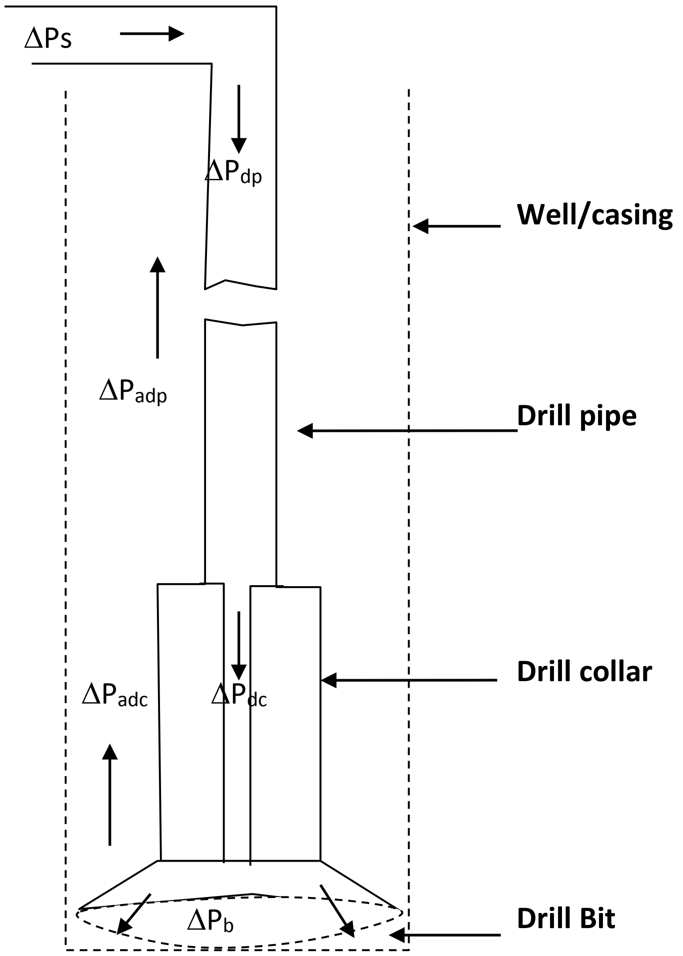

Figure 3.9: *Diagram of the well fluid system*

3.5.2 Unified pressure loss model

Table 3.3: illustrates the summary of rheological and hydraulic equation of the unified model in pipe and annular flow.

Table 3.3: Summary of rheological and hydraulic equation for Unified Model [37]

Pipe flow	Annular flow
$\mu_p = R_{600} - R_{300}$ $\tau_y = R_{300} - \mu_p$ $\boldsymbol{\mu_p = cp}$ $\boldsymbol{\tau = lbf/100ft^2}$	$\tau_o = 1.066(2R_3 - R_6)$
$N_p = 3.32\log(\frac{2\mu_p + \tau_y}{\mu_p + \tau_y})$ $K_p = 1.066(\frac{\mu_p + \tau_y}{511})$	$N_p = 3.32\log(\frac{2\mu_p + \tau_y - \tau_y}{\mu_p + \tau_y})$ $K_p = 1.066\left(\frac{\mu_p+\tau_y-\tau_o}{511}\right)$
$G = \left(\frac{(3-\alpha)n+1}{(4-\alpha)n}\right)\left(1+\frac{\alpha}{2}\right)$ $\boldsymbol{\alpha = 1\ for\ annuli}$ $\boldsymbol{\alpha = 1\ for\ pipe}$	
$v_p = \frac{24.51q}{D_p^2}$	$v_a = \frac{24.51q}{D_2^2 - D_1^2}$, $v = ft/min$
$\gamma_w = \frac{1.6*G*v}{D_R}$	$\gamma_w = sec^{-1}$
$\tau_w = \left[\left(\frac{4-\alpha}{3-\alpha}\right)^n \tau_o + k\gamma_w{}^n\right]$	$\boldsymbol{\tau_w = lbf/100ft^2}$
$N_{Re_p} = \frac{\rho v_p^2}{19.36\tau_w}$	$N_{Re_a} = \frac{\rho v_a^2}{19.36\tau_w}$
Laminar: $f_{laminar} = \frac{16}{N_{Re}}$ Transient: $f_{transient} = \frac{16N_{Re}}{(3470-1370n_p)^2}$ Turbulent: $a = \frac{\log\ n+3.93}{50}$, $b = \frac{1.75-\log n}{7}$ $\Big\}$ $f_{turbulent} = \frac{a}{N_{Re}{}^b}$	$f_{laminar} = \frac{16}{N_{Re}}$ $f_{transient} = \frac{16N_{Re}}{(3470 - 1370n_a)^2}$ Turbulent: $a = \frac{\log\ n+3.93}{50}$, $b = \frac{1.75-\log n}{7}$ $\Big\}$ $f_{turbulent} = \frac{a}{N_{Re}{}^b}$
$f_{partial} = \left(f_{transient}{}^{-8} + f_{turbulent}{}^{-8}\right)^{-1/8}$	
$f_P = \left(f_{partial}{}^{12} + f_{laminar}{}^{12}\right)^{1/12}$	$f_a = \left(f_{partial}{}^{12} + f_{laminar}{}^{12}\right)^{1/12}$
$\left(\frac{dp}{dL}\right) = 1.076\frac{f_p v_p{}^2 \rho}{10^5 D_p}$ **psi/ft** $\Delta P = \left(\frac{dp}{dL}\right)\Delta L$ psi	$\left(\frac{dp}{dL}\right) = 1.076\frac{f_a v_a{}^2 \rho}{10^5(D_2 - D_1}$ $\Delta P = \left(\frac{dp}{dL}\right)\Delta L$
$\Delta P_{Nozzles} = \frac{156pq^2}{(D_{N1}{}^2 + D_{N2}{}^2 + D_{N3}{}^2)^2}$	

4 DRILL STRING MECHANICS SIMULATION STUDY

4.1- Introduction

In general, rising development costs is one of major challenges facing the petroleum industry. During recent years several studies and experimental have been conducted to achieve the efficient recovery of oil and reduce the cost of drilling operation. As mentioned on the literature review, slim hole drilling have resulted proving to among the most effective concepts by reducing the drilling cost. In preceding chapters, a literature review of slim hole as well as theory related to torque, drag, hole cleaning and hydraulics were reviewed. To combat the increasing development cost one has to put more emphasis on the well design process during the drilling operation.

In order to evaluate the application of slim hole, this section presents several simulation studies on the load carrying capacity and stress in the drill string.

For the qualification of drill string mechanics, three simulations were considered. These are torque, drag and Von-mises stress. For a given operational conditions, if three loads are within the allowable window, it is then possible to uses the selected drill string. The safe operational window is bounded between the buckling, tensile, torsional limits.

The qualified systems presented in this section, are after doing several simulations with low grade drill string. The results of the low grade strings for most cases show failure and are attached in Appendix C.

4.2 Shallow and ultra-deep slim hole-Kuwait

4.2.1 Well profile and objectives

The six Field in Northern Kuwait has been considered too fast track production of gas/light oil from deep HPHT Jurassic reservoirs launched by Kuwait Oil Company (KOC). Prior to these, the objective of the venture is to access production of gas and light oil to these northern fields to 1000 MMscf/d gas and 350000 bbl/d by the year 2015. The challenge of wellbore construction in these northern fields is reaching with total depth of 15000 to 17000ft with pressure of 10000psi and temperature of 280°F.

It is a deep HPHT exploratory well that require a large-hole casing design to isolate problematic formations and to reach the target zones with maximum hole size. The surface and intermediate sections are drilled with larger diameter bits ranging from 28-in to 16-inch. The casing plan of the conventional well starts up from 30-inch casing conductor and ends with 5-inch liner. The target zone from Zubair to Hith was one of the most difficult/problematic hole sections. It was traditionally drilled with 16-inch bits and the formations consists of abrasive sandstone, reactive shale, limestone and anhydrites with UCS that varies between 5-30kpsi. The sections are divided into three basic sections: Upper Zubair Formation, Middle Ratawi Shale and Lower Ratawi Limestone to Hith.

Since the most crucial section is the Zubair to Hith, the drilling team considered to redesign the wells to use smaller casing and liner best suited for the smaller development rig's capacities. Prior to these and to reduce the cost, the KOC development and bit provider's engineering developed the first slim hole well plan and casing string design to explore Cretaceous formation in Northern Kuwait. With previous large hole design, the study determined the 7 ¾-in casing shoe to be set at around 13625ft and 10 ¾-in shoe was set at 9745ft at roughly 150ft into Zubair formation. The drilling team were able successfully downsize the hole/casing size **[39]**.

The company achieved saving the drilling operation by 55 % drilling time and over $1 million USD compared to the large hole and liner-string design due to the downsizing strategy and change in casing string design. In addition, the entire operation was completed with zero HSE related complications. Therefore, slim hole technology promises reducing cost from a downsizing and change in casing standpoint with regarding to the field results from this project.

Hence, the operation was completed successfully achieving the desired isolation in the zones of interest.

Figure 1 - General location and field specific map

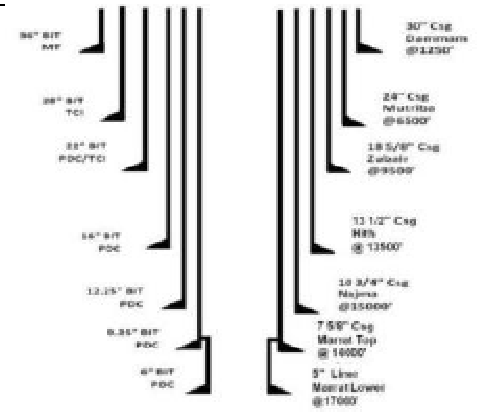

Figure 2 - Typical deep well casing program

SYSTEM	FORMATION	LITHOLOGY
Tertiary	Kuwait Series	Sands and Gravels
	Dammam	Highly fractured Limestone
	Rus	Anhydrite with Limestone
	Radhuma	Dolomitic Limestone
Cretaceous	Tayarat	Dolomitic Limestone with Shale
	Hartha	Medium hard Limestone
	Sadi	Soft to medium vuggy Limestone
	Mutriba	Medium hard Limestone
	Mishref	Medium hard Limestone
	Rumaila	Medium hard Limestone
	Ahmadi	Shale with interbedded Limestone
	Wara	Shale with interbedded Limestone
	Mauddud	Limestone w
	Burgan	Sandstone
	Shuaiba	Highly fractured Dolomitic Limestone
	Zubair	Sandstone interbedded with Shale
	Ratawi Shale	Shale
	Ratawi Limestone	Limestone
	Minagish	Dolomitic to Oolitic Limestone
	Makhul	Hard Limestone
Jurassic	Hith	Anhydrite interbedded with Limestone
	Gotina	Anhydrite and Salt layers
	Najmah	Fractured Limestone
	Sargelu	Limestone to Calcareous Shale
	Marrat	Oolitic Limestone with thin Shale

Figure 3 - Stratigraphic column with formation name and lithology type

***Figure 4.1**: Geological area and the typical deep well casing program [39]*

In this section, an attempt to evaluate the field data of these wellbore construction well will be analyzed by using WellPlan Software. The objective was to re-design the wells to smaller diameter hole compared with the standard well construction. Secondly, to investigate the torque and drag analysis for conditions tripping in, tripping out and stresses in the drill string.

The parameters data needed for this simulation study is not as accurate to the measured data in the wells. However, the torque and drag model was adjusted to measured data, either by changing some file data such as the friction factors, the weight of drilling pipe, the bit-type and the grade of the casing. We used a wellpath planning program to calculate the survey data for a Deep slim well, simulating of the old conventional well by changing the MD with new Measured Depth. The intent when creating the data set of this study has been to determine if the design is in safe operational window (buckling and tensile limits, Drag and Torque, stress in the drill string).

4.2.2-Simulation arrangement for shallow and ultra-deep slim

4.2.2.1-Drill string design

Drill string editor is related to the cased and open hole specification. The hole section editor requires the specific dimensions of the cased and open hole which includes measured depth, the length, inside diameter, weight and item description such as the Grade by API casing as well as the friction coefficient. Table 4.1-shows the drill string strategy that calculates all required input information to design shallow slim hole well (13630). As well table 4.2 has same input information that considers the key issues related to friction factors for designing torque and drag on slim hole well design on 20000ft. For instance, the friction factor that is applied on ultra-deep simulation operation is 0.25 for cased hole and 0.30 for open hole. This is the simulation arrangement that guides to model torque, drag and Stresses in drill string. The values required in the hole section editor are shown on the tables below.

***Table 4.1**: Hole section editor for slim hole well design for 13630 ft*

Hole Section Depth (MD): 13630,0 ft   Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	9770,0	9770,00	9,250	9,250	12,250	0,25	0,0831	7 in, 17 ppf, H-40,
2	Open Hole	13630,0	3860,00	5,875		6,915	0,40	0,0465	

***Table 4.2:** Hole section editor for slim hole well for 20000 ft*

Hole Section Depth (MD): 20000,0 ft   Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	17000,0	17000,00	7,025	6,900	6,250	0,25	0,0480	7 5/8 in, 24 ppf, H-40,
2	Open Hole	20000,0	3000,00	6,500		6,500	0,30	0,0410	

4.2.2.2-Drill Pipe and Bottom Hole Assembly Design table

Table 4.3 and 4.4 is related to the drill string specification (**Drill Pipe + BHA**). The Drill pipe requires the specific dimensions such as inside diameter, outside diameter, length of the drill pipe, density of the pipe, grade and connection. As it can be also seen from the table, bottom hole assembly consisting such as jar, sub, heavy weight and bit specification has been pre-entered. The user can choose the drill string assembly specification that are suited to the simulation study. It is possible to select or change any particular tool in the bottom hole assembly by clicking the row. The values that required to enter in appropriate rows and Column are not calculated automatic by the program but it is assumed values that is used. These values uses the program to design torque, drag and stresses in the drill string. It is not only used on this situation but it is essential for also evaluation process on hole cleaning. Table 4.3 shows the drill pipe and BHA specification entered for the shallow slim hole well to obtain torque, drag and stresses plot. , while table 4.4 is the data information implemented to design slim hole for 20000ft.

Table 4.3: *String editor for slim hole for 13630 ft*

String (MD): 13630,0 ft Specify: Top to Bottom Import String Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	13146,50	13146,5	4,500	3,958	15,21	Drill Pipe 4 1/2 in, 13.75 ppf, E, H90, P
2	Heavy Weight	120,00	13266,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
3	Jar	32,00	13298,5	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
4	Heavy Weight	305,00	13603,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
5	Sub	3,00	13606,5	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
6	MWD	22,50	13629,0	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
7	Bit	1,00	13630,0	5,875		33,00	Tri-Cone Bit, 3x16, 0,589 in²

Table 4.4: *String editor for slim hole for 20000ft*

String (MD): 20000,0 ft Specify: Top to Bottom Import String Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	19516,50	19516,5	3,500	2,764	14,69	Drill Pipe 3 1/2 in, 13.30 ppf, S, NC38(IF), P
2	Heavy Weight	120,00	19636,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
3	Jar	32,00	19668,5	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
4	Heavy Weight	305,00	19973,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
5	Sub	3,00	19976,5	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
6	MWD	22,50	19999,0	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
7	Bit	Component length	20000,0	6,500		33,00	Tri-Cone Bit, 3x16, 0,589 in²

4.2.2.3- Geothermal gradient

According to the oilfield glossary, geothermal gradient is the rate of increase in temperature with the respect to the increasing depth in the earth. It is important for drilling engineers to know about the gradient when designing particularly a deep well because the temperature and pressure increases per unit depth in the earth. The formation temperature can be found by adding the surface to the product of the depth and the geothermal gradient and can be expressed as:

$$\boldsymbol{T}_{formation} = \boldsymbol{T}_{surface} + \boldsymbol{D}\boldsymbol{\nabla}_{\boldsymbol{T}}$$

Figure 4.2 shows the geothermal gradient which increases by1.5° $F/100ft$. As it can be seen from the figure, the bottom hole temperature is 350°F and the surface temperature is 80°F.

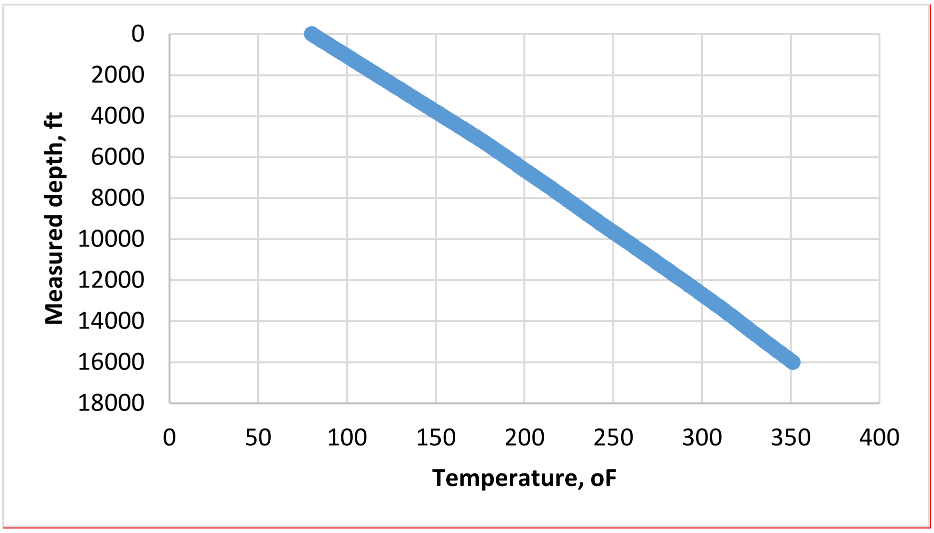

Figure 4.2: *Geothermal gradient graph (Measured depth vs Temperature)*

4.2.2.4-Drilling fluid editor

Figure 4.3 shows the measured viscometer data of the fluid system. The plastic and yield stress of the fluid systems are 40cP and 18lbf/100sqft respectively. The density of the fluid is 1.75sg.

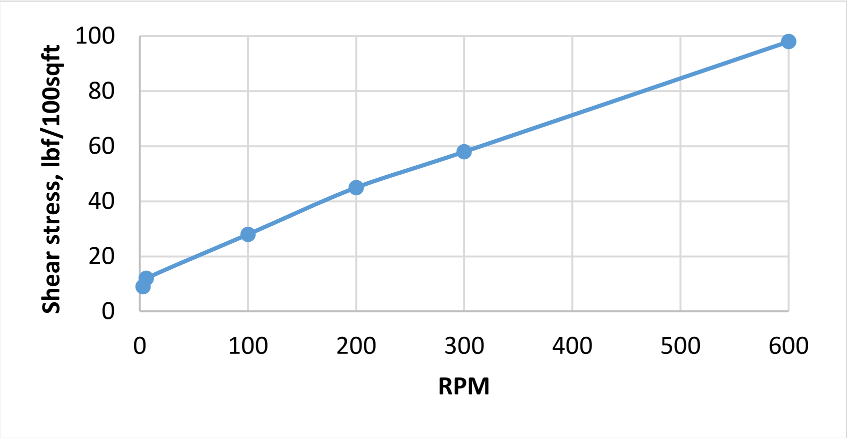

Figure 4.3: *Viscometer data of drilling fluid*

4.2.2.5- Well Structure

This section presents the well structure. Figure 4.4 and Figure 4.5 show the well geometry of shallow-slim and ultra-deep slim well along with the strings, respectively. The survey data, dogleg severity, well inclination and azimuths of the wells are given in Appendix A.

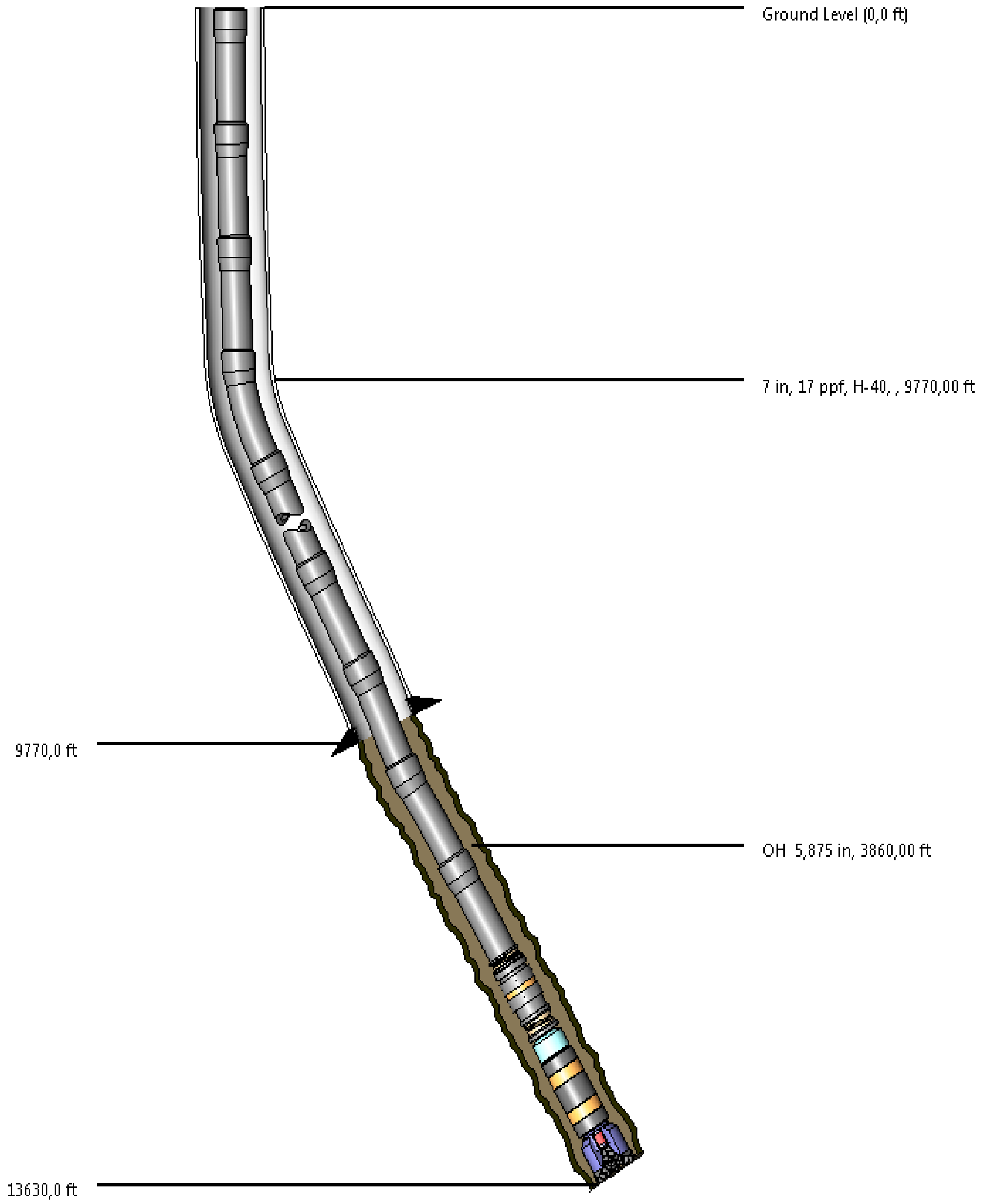

Figure 4.4: *Field case, Well schematic*

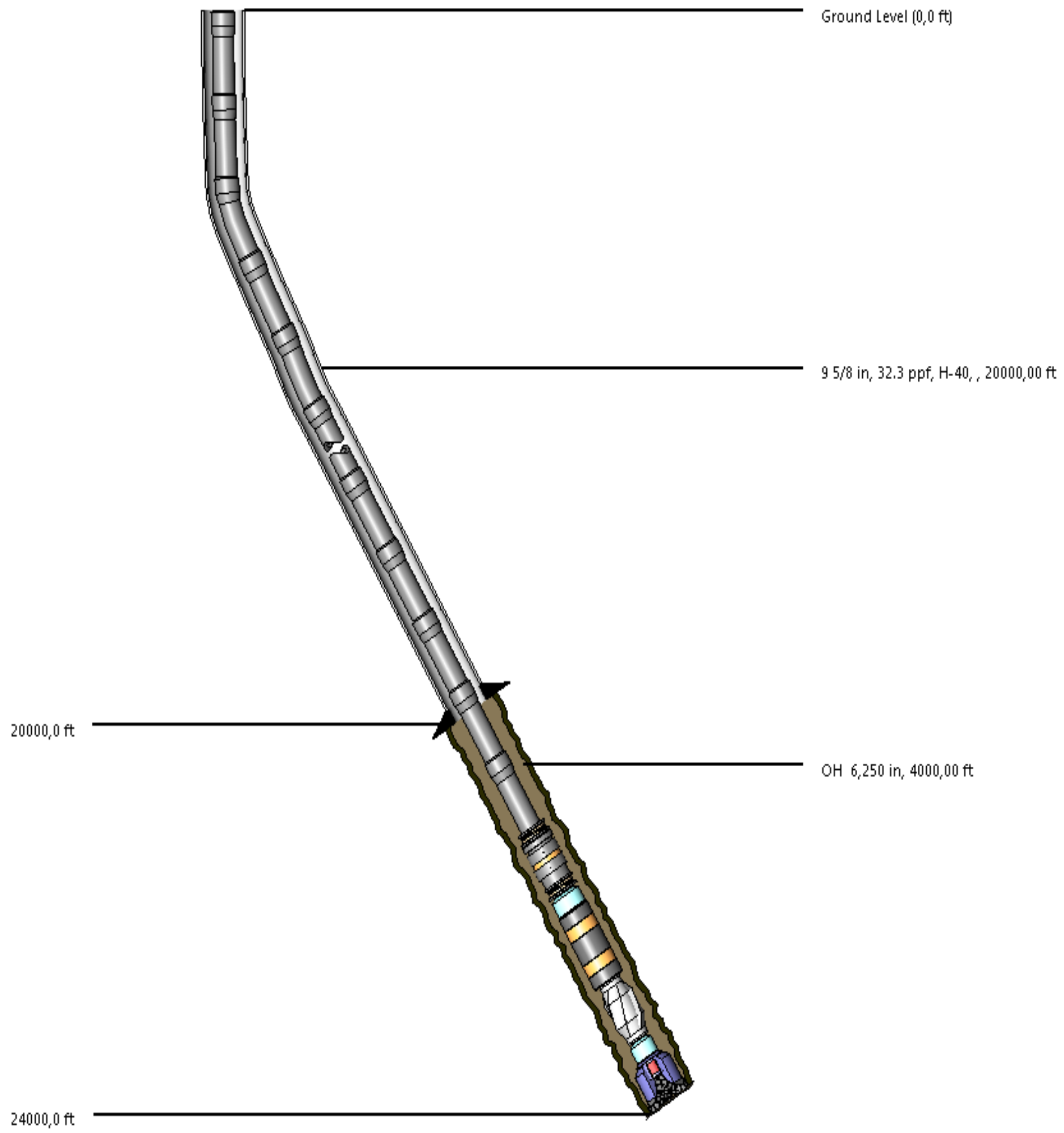

Figure 4.5: *Well configuration used for ultra-deep well scenario.*

4.2.3-Simulation result for shallow-slim hole well (13630 ft)

Torque and drag analysis plays an important role in drillings operation. In this analysis is performed using Landmark's WellPlan torque and drag. In previous sections had been provided the inputs necessary for this simulation. During the simulation process when applied different scenarios is presented to answer "Will torque and drag design exceed the operating limit for the proposed well friction coefficients and Grades"?

For determination whether the design is in the safe operational window, torque drag effective tension graph should be used. For stress analysis, true tension should only be used.
The outputs observed from the torque drag effective graph consists the following curves:

- Tension limit
- Helical Buckling (rotating)
- Tripping out/in

In this section, we have simulated both conventional and slim hole based on the Kuwait field. It is presented different scenarios to see the changes that is made until technically feasible well design is achieved. During this simulation we assumed a worst case scenario such that cutting and well collapse could increase the friction coefficient. Therefore, the well-drilling coefficient of friction was assumed to be 0.20 for the drill string casing and 0.40 for open hole.

The simulation result with the conventional shows that during tripping out with E-grade drill string reaches to yielding at the top section. The same problem also observed on torque graph. The results are shown on Appendix C.

In order to solve the problem, it is been considered to change the friction factors by assuming for the value of open hole as 0.30 and kept unchanged for cased hole equal to 0.20. The objective was to investigate out if it will affect the normal torque drag and tension graph. It has been found that the change of friction factor had a little impact on new design as the outputs passes through the tensile limit. Therefore, it is proposed to use a higher grade (G-grade) on the top section and E-grade on the lower part of the drill string. The combination of E-grade and G-grade solved the problem.

As result of this, the plots are shown on Appendix-C which indicates that all the operation curves falls to the right tension limit curve. Therefore, it is predicted not to occur a problem since the new design is in the safe operational window.

Similarly the slim hole was simulated based on similar well conditions. The results are shown in the following figures. Figure 4.6- shows the effective tension distribution along the drillstring for tripping in/out from surface to depth 13630 ft. The well schematic is same as that depicted in figure 4.4. The drillstring configuration are given in table 4.1 and 4.3.
As it can be observed from the graph, it is noticed that tripping out operation is closely the tension limit at the surface resulting in the very low overpull margin. Both figure 4.6 and figure 4.7 illustrates that the drill string is in a safe operational window since it does not cross the tension and torque limit.

Drag result

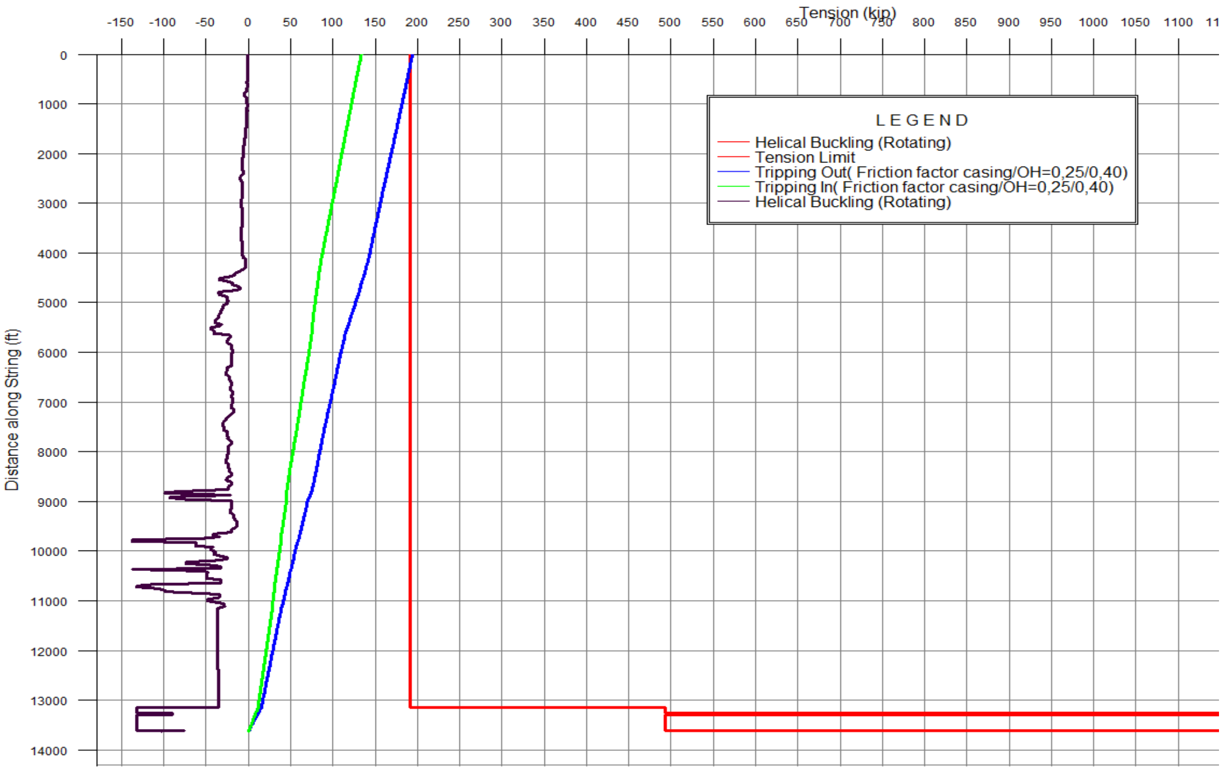

Figure 4.6: *Drag effective tension graph for shallow-slim hole well design*

Torque result

Figure 4.7- shows torque graph simulated for tripping in, tripping out and rotating on bottom. The data are given in table 4.1 and 4.3.The left side of the curve is the 1000ft-lbf torsional limit. As it can be observed from the figure, at depth of 1360 ft, the torque on bit is 0 ft-lbf on both tripping in/out operations. However, when landing the drillbit at the surface, it shows an increase of torque force to 6500 ft-lbf when tripping in while it indicates an increase around 9200 ft-lbf when tripping out.

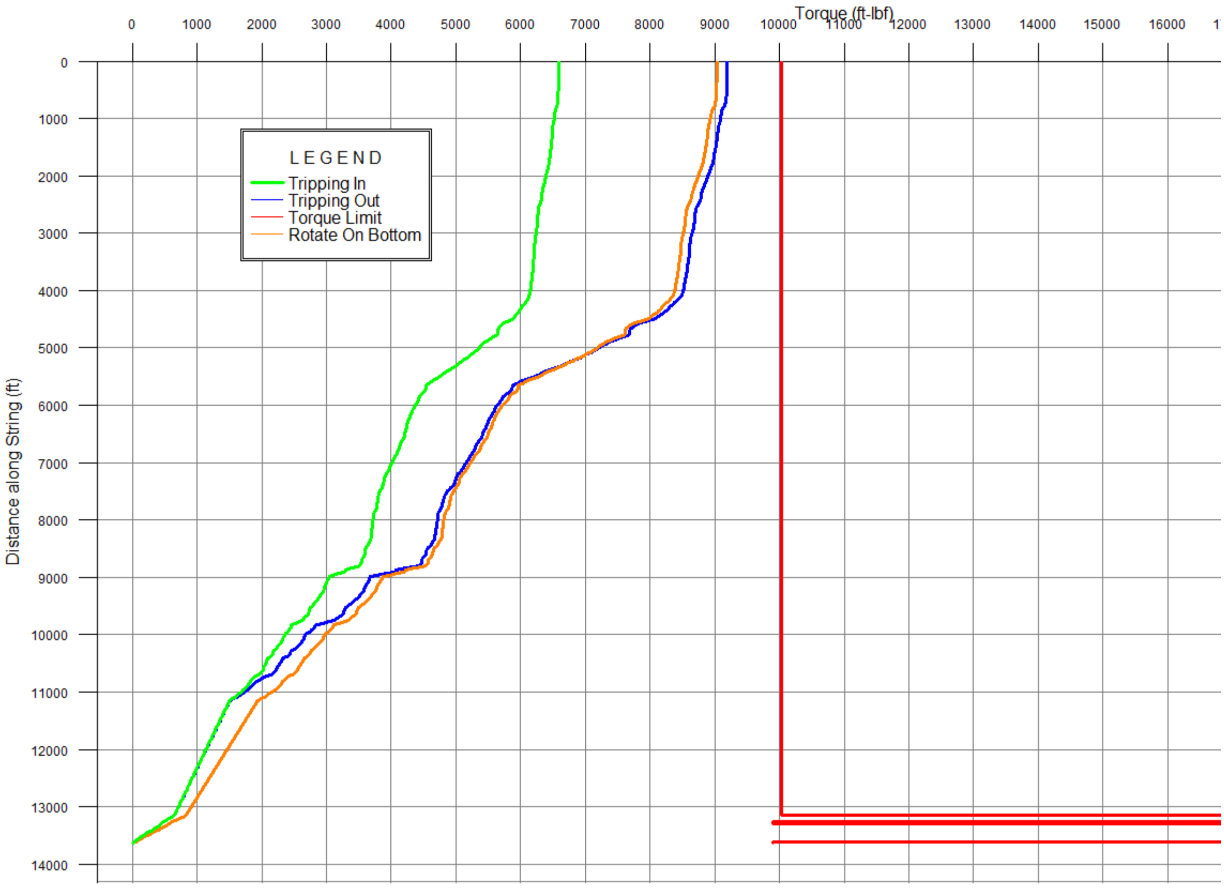

Figure 4.7: *Torque graph for shallow-slim hole well design*

Stress in drill string result

Load on drill string creates stresses in drilling string. The stresses are in the radial, tangential and in the axial directions. The loads are due to by the applied dynamic pressure in and outside of the drill string. These are a function of static mud weight and the dynamic friction due to fluid flows. The axial external loads and due to bending contribute to the axial stresses. The applied torque generate shear stress in the drill string. All of these stresses are used in Von-Mises failure criteria. Drill string fails when the stress drill string (Von-Mises) reaches to the yield strength of the drill string. The theory is presented in section 3.3.
To evaluate the condition of drill string in the slimhole, the Von-Mises stress was calculated using equation 3.2 reviewed in section 3.

Figure 4.8 shows von-mises stress in drill string. Von-mises simulation was for 300gpm flow rate. The result that the stress is within the stress limit.

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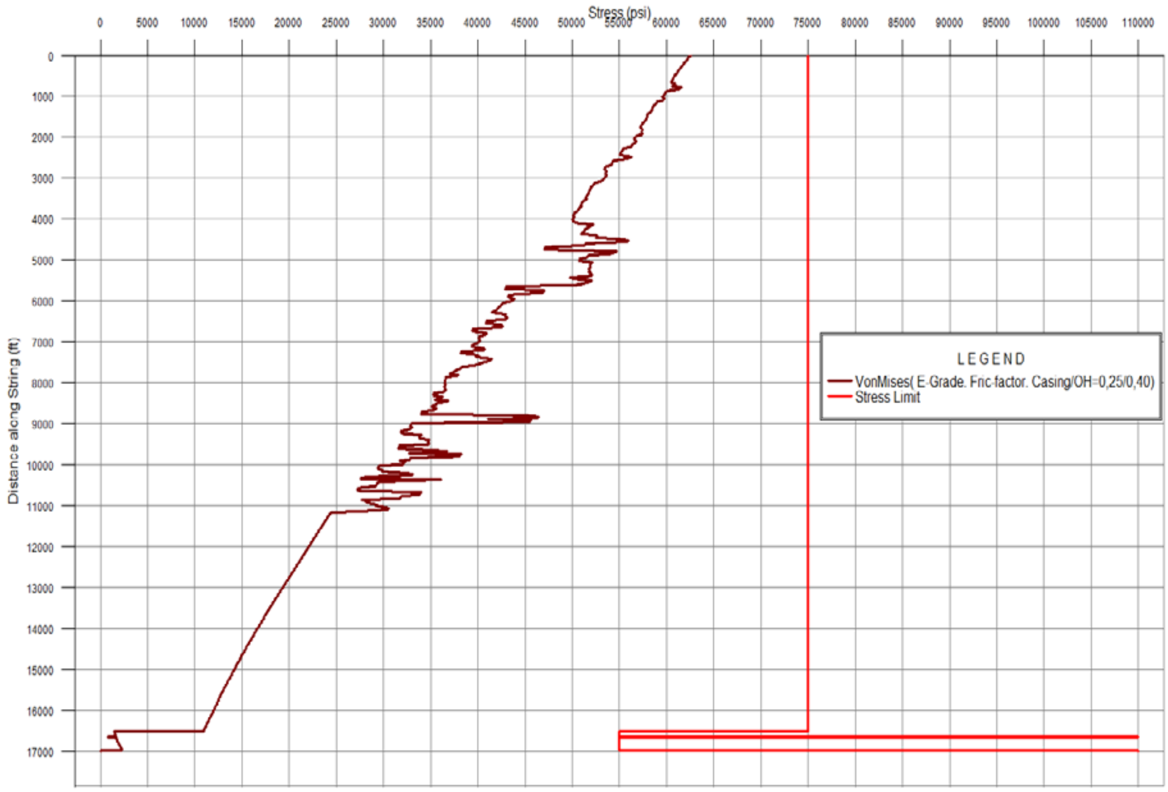


***Figure 4.8:** Stresses in Drill string For slim Hole Design at flow rate = 300 gpm*

4.2.4- Simulation result and analysis for ultra-deep-20000 ft

One of the research question raised in problem formulation was how far one can drill with slim hole?

To investigate this, at first 24000ft long well were considered. The well and drill string, and drilling fluid information are presented in Appendix C-1. The torque and drag, and stress result are presented in appendix C-1. The result reshows that this well length, the selected drill string cannot carry the loads.

The second attempt was made by reducing the well depth to 2000ft. For this well, all the input data are identical with the wellbore profile mentioned earlier except the changes made on the well depth. The same friction factor is applied as the cased hole is equal to 0.25 and 0.30 for open hole. In tables 4.2 and 4.3- are presented the hole section editor and drill string data. In order to fulfill the task, it was decided to perform simulation study to analyze the torque, drag and stresses during the drilling operation.

Drag on drill string

Figure 4.9- Displays the tension for the drill string versus measured well depth along the drill string. The negative value indicates the compression force while the positive values shows the tension in the drill string. The red line to the right represents the tension limit when while the grey line to the left shows helical buckling limit when there is rotation. For the tripping in/out operations, the tension in the drill string is at highest level on the surface (150/300 kip) .

The drag plot also indicates that all the operations, tripping in/out are between the drill string buckling and tensile limit, meaning it is operating in the safe window. After simulating with lower grades such as G and E-grade, it is been found that the drill string passes the tensile limit. Therefore, it is been considered the S-grade. Even though this grade is more expensive, it is recognized as the most suitable grade for this ultra-deep slim hole simulation.

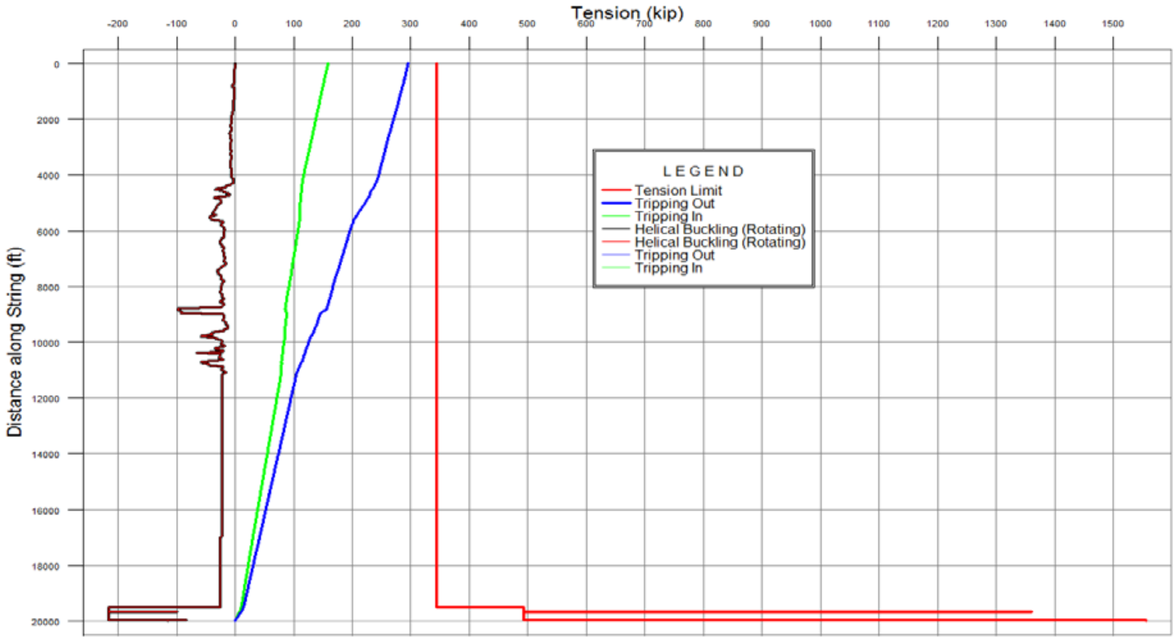


Figure 4.9: Effective tension for ultra-deep slim well

Torque

Figure 4.10- shows the torque graph obtained from the wellplan simulation. The green curve represents the drillstring when tripping in while the blue curve shows it is tripping out. As it can be seen from the figure, the torques obtained from the two operations are within the safe window.

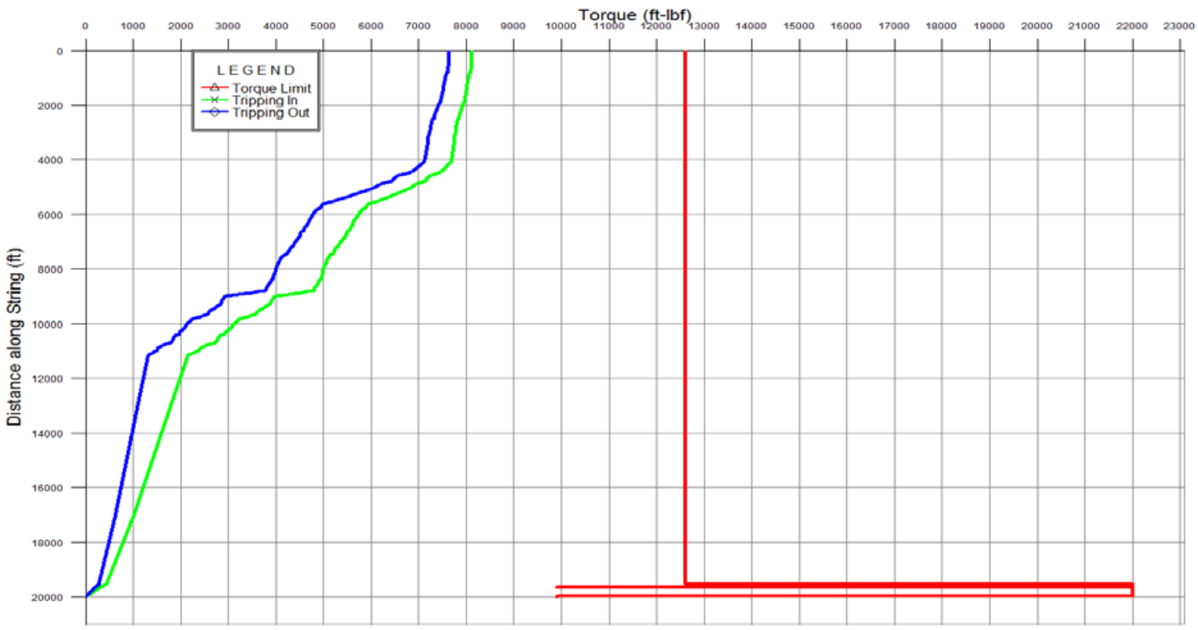


Figure 4.10: Effective torque graph for slim well

Stress in drill string

Figure 4.11- shows the stress during tripping in and Figure shows the stresses during tripping out. As shown on the figures, in both cases the stress in with in the safe window.

Based on the three simulations result. Slim hole can be drilled up to 20000ft provided that the drill string is a higher quality, which is S-Grade. However for the lower grade qualities, which as E-and G-grades, the length should be 17000ft as shown in section 4.3.

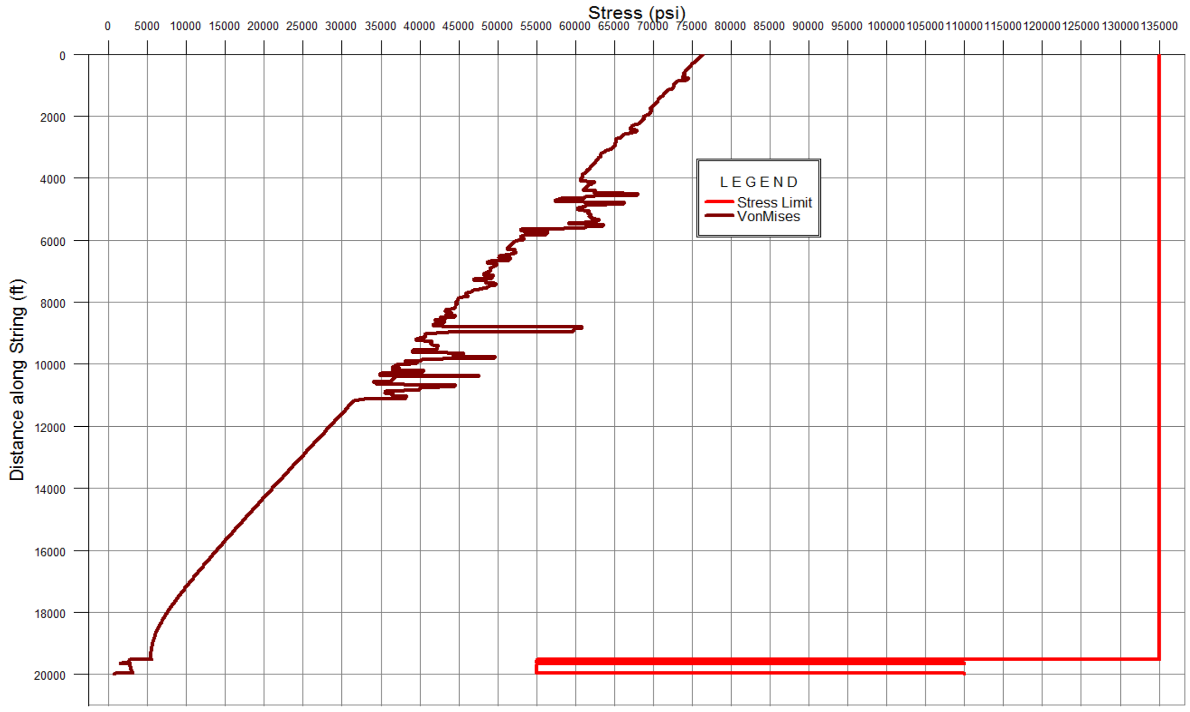


Figure 4.11: *Von-Mises stresses tripping in operation*

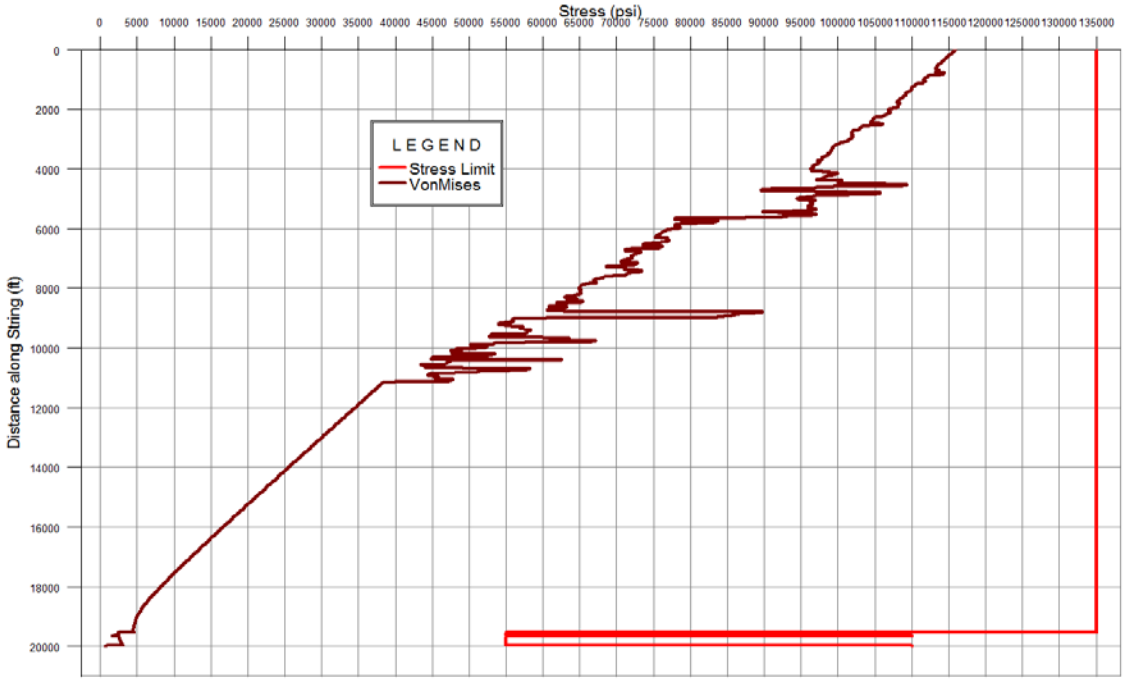


Figure 4.12: *Von-Mises stresses tripping in operation*

4.3 Deep slim hole-Carter Creek Field -USA

This well is a slim well drilled in the Carter Creek Field in Southwest Wyoming and was discovered by Chevron In 1977. The True Vertical Depth is 15000 ft and the measured depth of this well is +/- 17000 ft. The characteristic of the area such as extremely hard, abrasive formation, plastic salt and steeply dipping beds have presented many challenges to the operators. Due to this, it is required to 150-200 days to construct and drilling operation to +/- 17000 'MD. It had long been considered slim hole drilling at carter creek, planning a 6 –inch hole size at TD enabled the idea of an 8-1/2 –inch intermediate hole section with 7-inch casing. The surface casing being reduced to 9-5/8 –inch in a 12-1/4 –inch hole. Therefore, slim hole drilling has proven a valuable well design strategy by achieving cost saving due to such as smaller rig [**19].** The slim well has a simple well profile, with hole section shown in the following table. The torque and drag simulation was performed on 16000 ft deviated well geometry. Figure 4.13 shows a well schematic with around 6.5 inch drilling assembly used in this simulation.

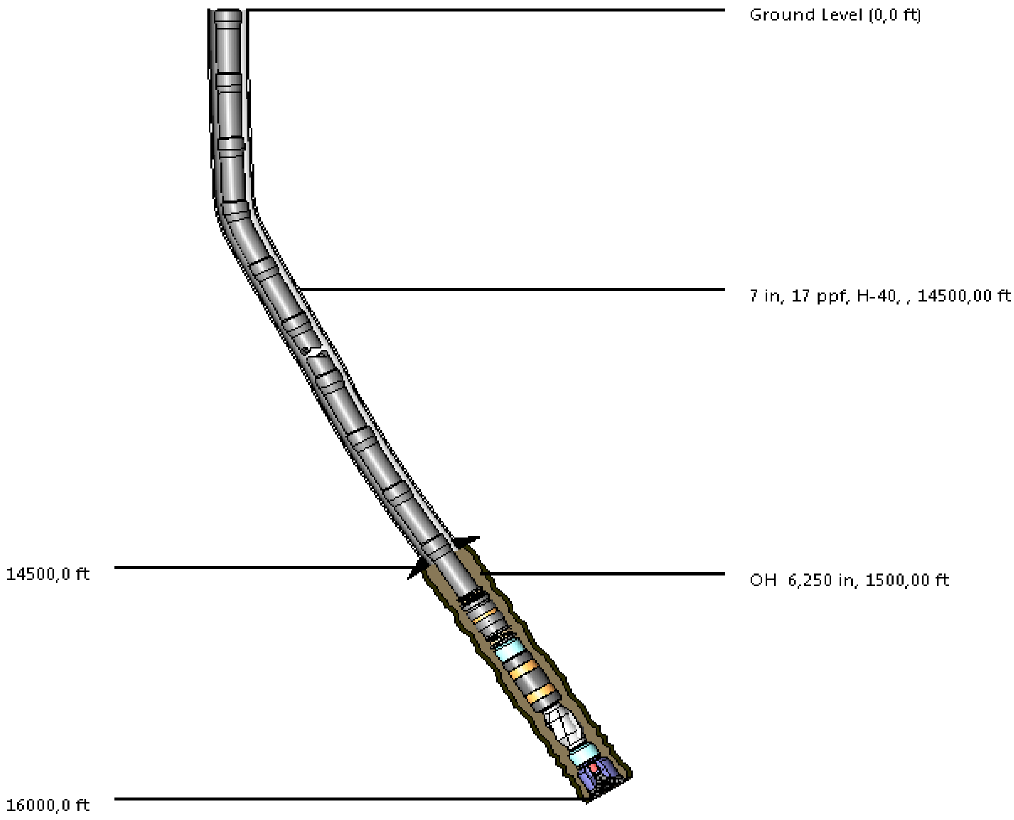


Figure 4.13: *Well schematic for deep slim hole well in Carter Creek Field*

4.3.1- Simulation arrangement

Table 4.5- shows the drillstring and borehole data used in this simulation. The industry will usually only allow a single friction factor for a given hole section. As seen on the table, it is only allowed for the entry of a single cased hole and single open hole friction factor. The hole section editor requires the specific dimensions of the cased and open hole which includes measured depth, the length, inside diameter, weight and item description such as the Grade by API casing as well as the friction coefficient

The borehole section is set the last casing and the open hole where the cased hole is 14500ft and the open hole is 1500ft length. As illustrated the below table, it can be noticed that the drilling string parts (Drill Pipe + BHA) is entered from top to bottom. Each section type follows up by filling in nominal diameter, weight and item description. the user needs to select the right parameter /value to enter in the appropriate column/row to use during simulation of torque, drag and stresses analysis. The intent of creating the input data was enable to display the perspective point of interest.

***Table 4.5**: Borehole and drillstring data used deep-slim hole well design*

Hole Section Editor

Hole Name: Hole Section | Import Hole Section

Hole Section Depth (MD): 16000,0 ft | Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	14500,0	14500,00	6,250	6,413	6,538	0,25	0,0379	7 in, 17 ppf, H-40,
2	Open Hole	16000,0	1500,00	6,250		6,555	0,25	0,0417	
3									

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	15508,50	15508,5	4,000	3,240	17,07	Drill Pipe 4 in, 15.70 ppf, E, H90, P
2	Heavy Weight	120,00	15628,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
3	Jar	32,00	15660,5	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
4	Heavy Weight	305,00	15965,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
5	Sub	3,00	15968,5	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
6	MWD	22,50	15991,0	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
7	Stabilizer	5,00	15996,0	3,250	1,500	22,22	Integral Blade Stabilizer 4 1/8" FG, 3 1/4x1 1/2 in
8	Sub	3,00	15999,0	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
9	Bit	1,00	16000,0	5,875		33,00	Tri-Cone Bit, 3x16, 0,589 in²
10							

4.3.2 Simulation results and discussion

The objective of this part of the simulation is to outline the drill string qualification procedure based on drill string mechanics. These are analysis of torque, drag and stress in drill string. The simulation controlling parameters are operation and flow rate and the coefficient of friction.

Before to use the slim hole simulation, it is important to determine how friction coefficients and flowrates could involve on designing tension, torque and stresses graph obtained from the wellplan software. Therefore, a scenario for a sensitivity analysis of the friction factor was considered during the simulation study. It could be helpful to analyze torque, drag and stresses for the slim well as operational perspective .At the same time, one should try to obtain an acceptable slim well design operational window from the wellplan software by inputs of different flowrates. Once the result predicts that it is within the safe operational window, then tripping in/out operation is moving under normal condition. On the other hand, if any problem occurs during the operation, a new friction coefficient or change of grade can be proposed.

Drag at 0.25/ 0.25 using 250 and 350 gpm flowrate

The effective tension plot is used for determination when the drillstring will buckle or fail due to tension. The blue line is the tripping out operation when used friction factor 0.25/0.25 with 350 gpm flow rate. The green line represents tripping out when used coefficient friction of 0.25/ 0.40 with 250 gpm flowrate. Figure 4.14- shows that the green line is closer to the tensile limit than the blue line which lies under the safe window. This indicates that by increasing the wellbore friction factor, the tension will increase. For instance, as it can be observed from the figure, the tension value decreased due to the decrease of coefficient factor when tripping out. At coefficient 0.25/0.25 shows that tripping out operation curve lies left to the tensile limit. Therefore, this does satisfy the requirements the parameters that are being used such as the flowrate 350 gpm.

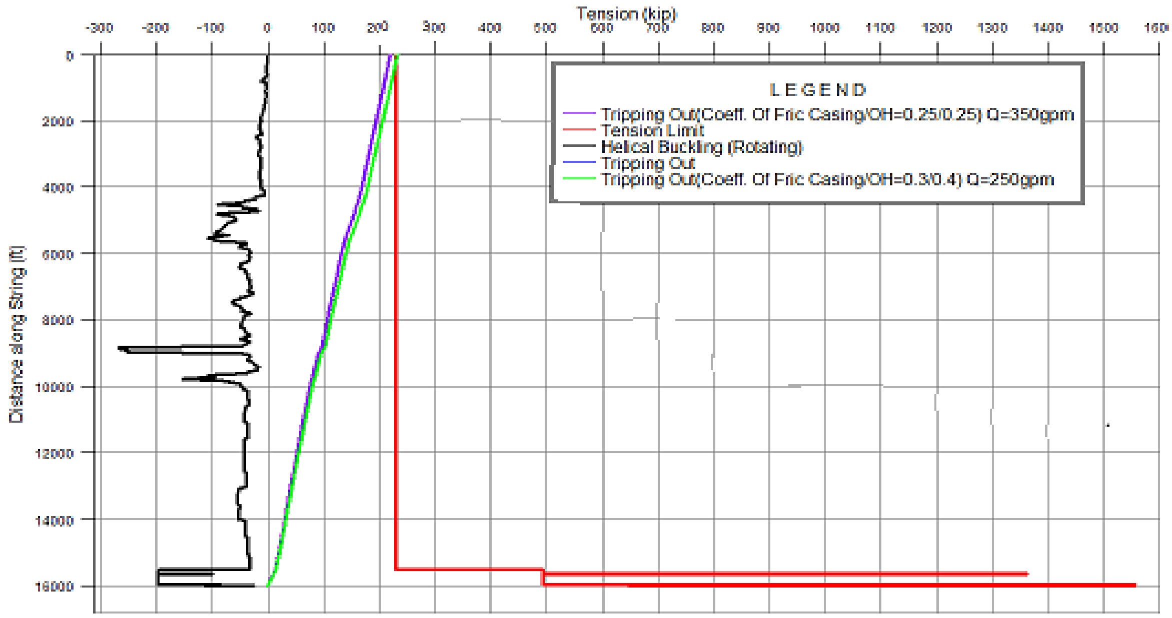


Figure 4.14: *Drag Effective Tension for slim well*

Torque at 0.25/ 0.25 applying 250 and 350 gpm flowrate

As mentioned on the drag discussion, by increasing the well friction coefficient, the tension value will increase. Similarly, the torque value will increase during tripping out due to decrease in flow rate. Figure 4.15-shows the effect of flowrate on the torque during tripping out operation at a constant coefficient friction on both cased and open hole. The drill string is in the safe operation window since it does not cross the torque limit.

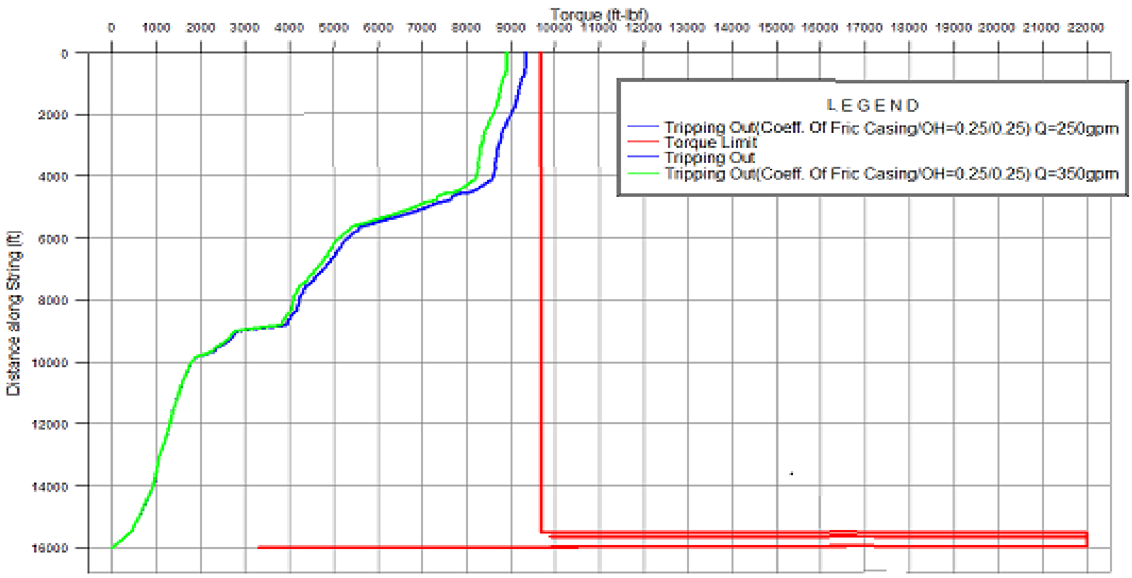


Figure 4.15: *effect of flowrate on torque during tripping out with 0.25/025 friction factor.*

Stress at 0.25/ 0.25 applying 250 and 350 gpm flowrate

Figure 4.16- The stress plot obtained from using 250gpm and 350 gpm flowrates, shows that VonMisses in both situation passes over the stress limit. Due to this reason , our model become risky to design. This observation tells us that for a flow rate higher than (250 and 350 gpm) may solve the problem of stresses on the drill string. As can be seen on the top part of von-mises, the stess reaching the line. However, it is possible to make a wider window by combining a higher grade (G-grade or S-Grade) on top section with the lower grade (E-Grade).

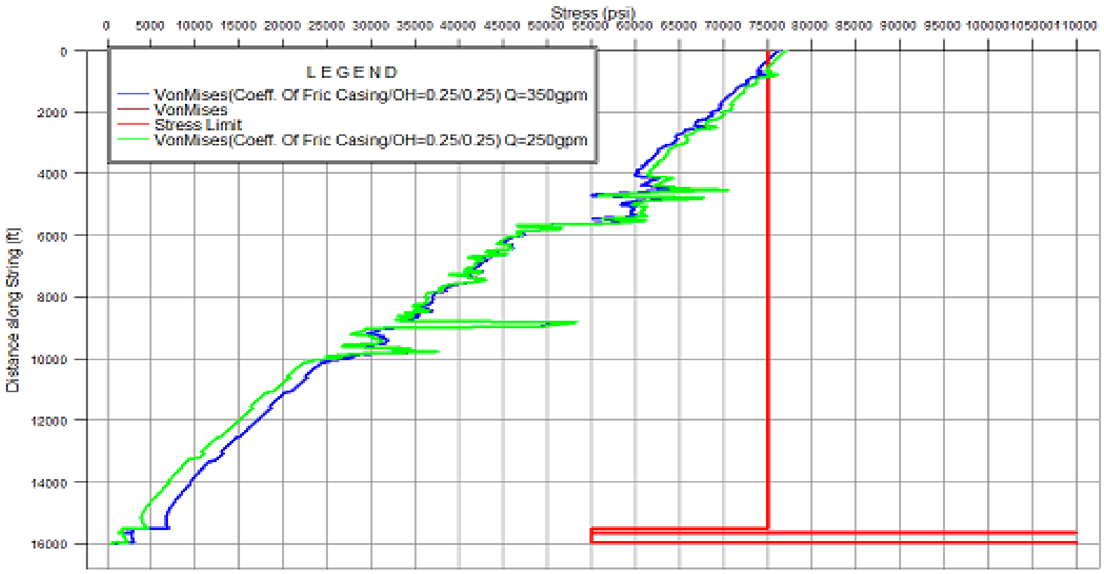


***Figure 4.16**: Von-Mises Stress with flow rate 250 and 350 gpm.*

Any well planning should be run torque, drag and stress in order to qualify the procedure based on operational perspective. It is important to evaluate different values of CoFs, flow rate and rotation speed in worst-case scenario to ensure the drill string can be within the safe operation window.

As brief conclusion, if the well friction coefficient will be increased at lower flow rate during tripping out operation, it will result higher tension value (see Figure 4.14). Additionally, it is been noticed that the lower flowrate at constant friction factor will decrease the torque value along the drill string at the surface (See figure 4.15). Hence, the entire drill string both drag and torque are on the safe operational window on this conditions which satisfies the slimhole well design requirement. During the simulation, the effect of rotation speed was investigated. It is been found that higher RPM with higher flow rate results lower tension and torque value. Again the similar conditions were used on the stress graph. The results shows that it crosses the stress limit. In this case, it is recognized that it has no effect on our stress graph. However, after simulating with higher flow rate for example 600 gpm, it is been observed that that the Von-

Misses stays within the stress limit. It is recognized that flow rate has more effect on stresses than drag and torque values during tripping out operation on slim hole well design.

The aim for this section was to evaluate different parameters in order to have a reasonable result for torque, drag and stresses on drillstring for slimhole well design. Therefore, to be able to have a reasonable results, it is been considered the effect of changing the grade on torque, drag and stresses simulation. The objective was to develop a qualification for slim well to select the type of G-grade drillstring. As mentioned on the theory section, many studies have shown that friction factor can be adjusted depending on analysis which is applied on drag, torque and stress simulation on drillstring. Currently on this section, it is b assumed different friction factor compared to the previous section as:

- 0.25- for cased hole
- 0.30- for an open hole

As it can been seen from the new plots, the change of COFs and the grading qualified for this slim hole well geometry is qualified as expected the outputs to remain in the safe operational window. Figure 4.17- shows that the drillstring is safe since it does not pass the tensile limit during tripping out when applied with higher grade than E-grade.

Figure 4.18- shows torque plot when used G-grade.The torque was simulated and checked the result accomplished during the tripping out/in, rotating on operations. It can be more clearly noticeable that all operations are shifted to left side of the torque limit indicating that torque at the surface decreases due to the higher grade. It may be conlcued that the drillstring is on the safe window according to applied frition factor and G-grade. Figure 4.19- indicates that with simulating flow rate at 600 gpm the Von-misses does not cross over the stress limit indicating that the model is a safe.

Slim hole drag plot for normal coefficient at casing=0.25 and OH=0.30

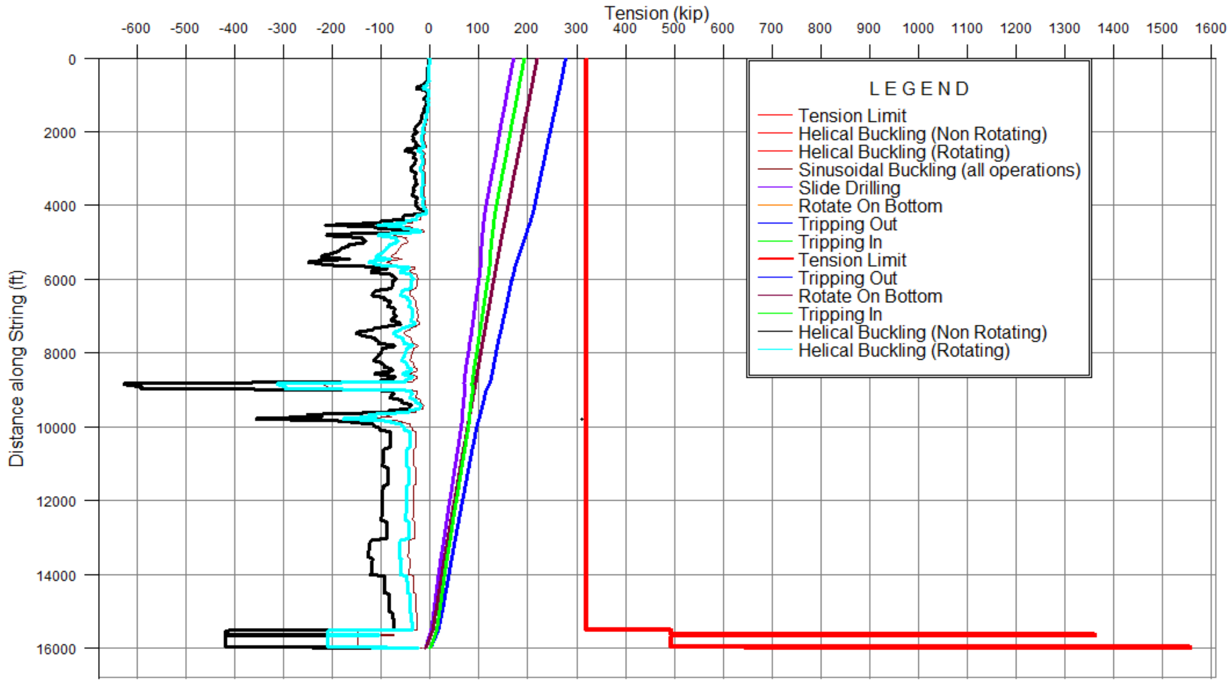


Figure 4.17: *Drag Effective plot simulated with G-grade*

Slim hole torque plot for Normal coefficient at casing= 0.25 and OH=0.30

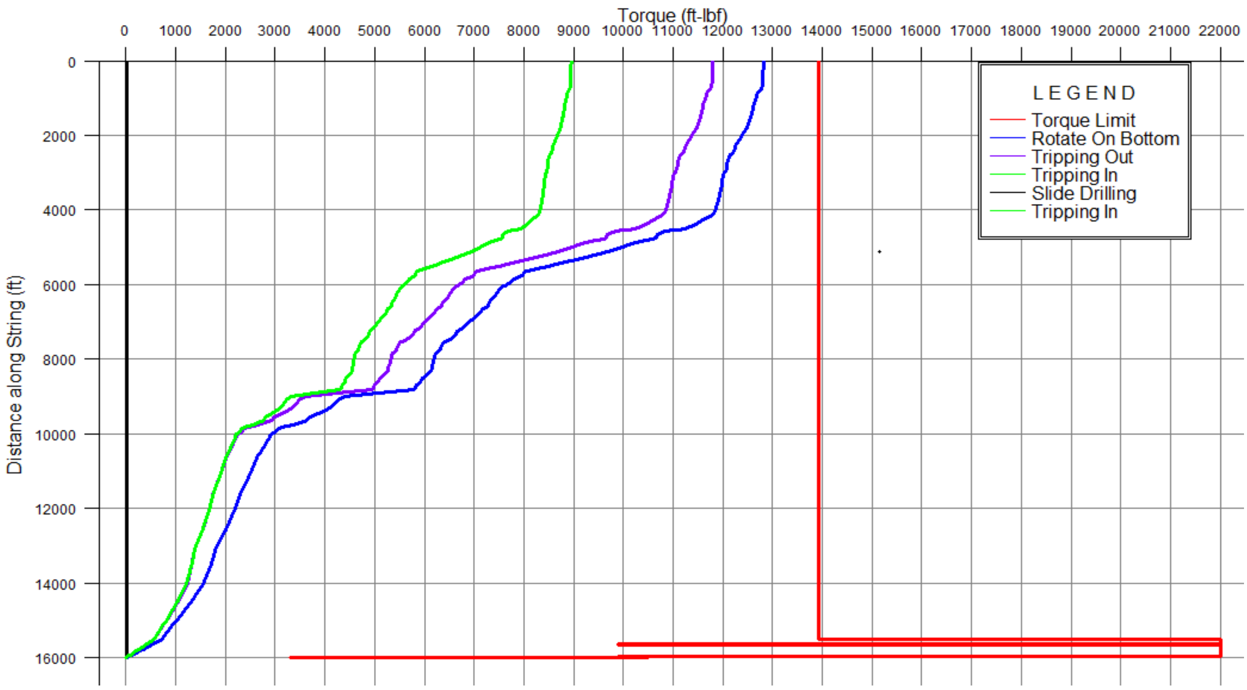


Figure 4.18: *Torque plot for the application of G-grade*

Slim hole stress plot for 600 gpm Normal coefficient of 0.25 and 0.30 friction .

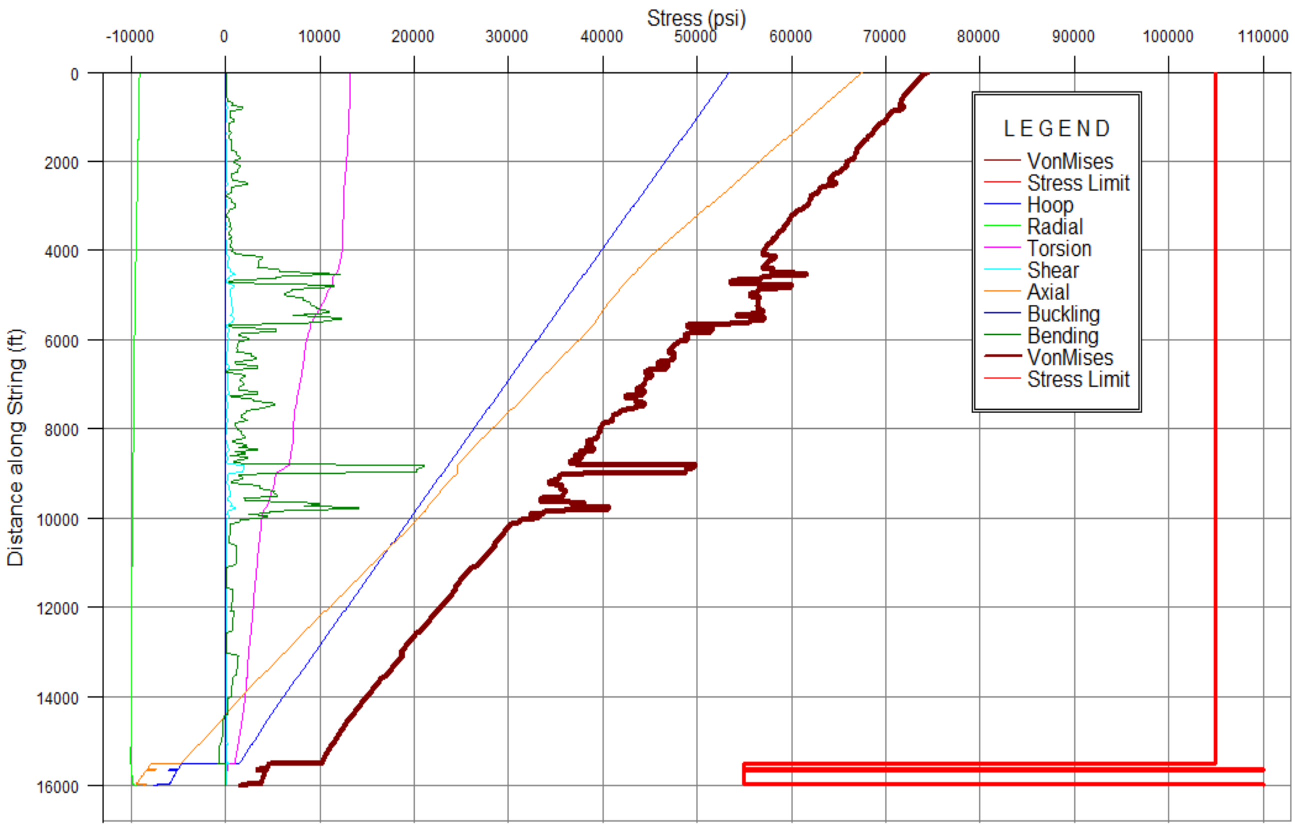


Figure 4.19: Von-Mises stresses when applied with flowrate at 600gpm and G-grade

5.0 Hydraulics and hole cleaning simulation study

This chapter presents simulation studies of slim hole with regards to hydraulics and hole cleaning efficiencies. The results are compared with a typical conventional well structure.

5.1 Hydraulics simulation

Hydraulics is an important issue to consider in drilling operation. Drilling slim holes means drilling small diameter holes that requires smaller drill-pipe, bits, and annular clearance. This will affect many interrelated issues around drilling fluids and the circulating pressure developed. The main functions of the circulating drilling fluid are to lift cuttings from beneath the drill bit to the surface, maintain the hydrostatic pressure to avoid formation fluids from flowing into the well, and to keep the hole open and competent for subsequent drilling until casing is run. The drilling fluid is pumped through the surface lines, pipe, Kelly, down the drill string and bottom-hole assembly and then circulated back through the annulus and the surface mud treating system. Hydraulics can be expressed as the optimization of the rates and pressures of the drilling fluid through the system. For any drilling operation, hydraulic analysis is an important aspect. Because hydraulic optimization involves the careful analysis of the fluid properties and pipe, bit and hole geometries to optimize the end results of the interrelated drilling fluid functions such as increasing rate of penetration while keeping control of the well, a competent, in-gauge bore and preventing formation damage.[10]

The slim hole geometries has a smaller drill string, narrow annulus and higher rotating speed (positive effect for cutting transport) which create added sensitivities to the key hydraulics variable. Some of the consideration that can result from this, include:[10]

- Higher annular pressure because of the smaller annulus
- Increased Equivalent Circulating Density (ECD) due to higher annular friction (Risk of pipe sticking and lost circulation).
- The greater ECD sensitivity to flow rate changes because of the higher annular friction.
- The effect of rotary speed on annular friction and ECD is greater
- Higher rotating speed can create drill solids and weighting materials to place out inside of the drill pipe

Due to the above heightened sensitivities and narrow annulus in slim wells, it makes absolutely essential to study the pressure losses in the annulus and overall hydraulics by using accurate hydraulics models. . There are a several hydraulics models that can used to estimate pressure drops such as Bingham Plastic, Power law and Herschel Buckley in the Oil and Gas Fields. However, in this study, it is used to run the unified hydraulic model to analyze the pressure losses and ECD in both a slim-hole and conventional well.

In this chapter a hydraulic simulation study based on slim-hole drilling experience in Whitney Canyon Carter Creek Field, USA is presented. The aim for the Carter Creek Field was to drill Slim-hole well to enhance development drilling economic. Therefore, it is important to compare the hydraulics behavior for both conventional and slim-drilling. Hence, there is a big concern in the smaller diameter in the annulus of slim hole well because of the increase in annular friction pressure when pumped drilling fluid with higher flow rates. In slim-hole drilling case, we used the standard equipment and the data used in this study are summarized in the following table. In addition, a flow rate was selected as 0, 50, 100, 150,200, 250, 300,350, 400,450, 500,550 and 600 Gal/min.

5.1.1 Simulation arrangement

For this simulation a 16000ft long well with 6.5'' size were considered. The drill string is OD=4.5'' and ID =4.0". The system consists of three bits with 28'' size. Figure 5.1: shows an illustration of hydraulics simulation well.

Table 5.1: *Well geometry and mud properties data values*

	SLIM-HOLE DRILLING	CONVENTIONAL DRILLING
Depth (ft)	16 000	16 000
Mud Weight (ppg)	14.161	14.161
Drill Pipe OD (in.)	4.5	5.5
Drill Pipe ID (in.)	4.0	5.0
Bit Size (in.)	6.5	8.5
Md.PV (cp)	34 (From white & Zamora)	34
Md. YP (lb/100 ft)	24 (From white & Zamora)	24

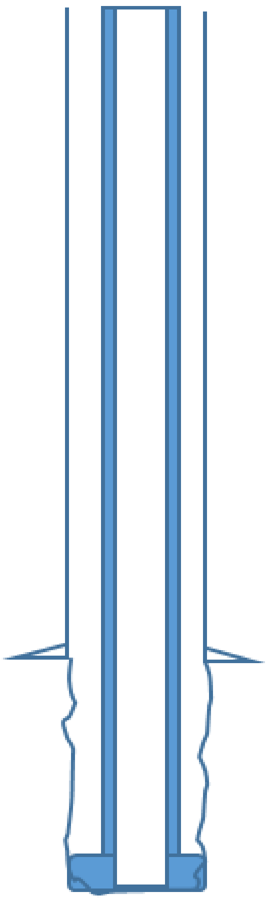


Figure 5.1: Illustration of simulation well

Drilling fluids

The rheological mode used was unified model based on R3-R100 and R300-R600 readings. Table 5.2-represents rheological properties used in this simulation.

Table 5.2: Rheological properties from Fann70

RPM	Viscous Drilling Fluid	Less Viscous Drilling Fluid
600	92	73,6
300	58	46,4
200	46	38,6
100	32	25,6
6	10	8
3	8	6,4
Density, PPG	14,1	11,3

5.1.2 Simulation result

This section presents the simulation results of pump and annular pressure loses. In addition, the ECD was calculated. For the simulation Unified model presented in Table 3.3 was used.

5.1.2.1 Pump and annular pressures in slim and conventional well

In Figure 5.2: shows the behavior of pressure drop loss versus the flow rate. This simulation is based on only the viscous fluid shown in table 5.2. Since the difference between conventional and slim-hole wells is the annular volume, understanding the pressure loss at the annulus is an essential for well stability and thus to reach a successful drilling operation. Hole pressure losses are simulated for the different flow rate using the unified hydraulic model. As it can be observed from the figure the pressure drops are greater in slim hole well as the flow rate increases compared with conventional well. For instance, the effect of flow rate at 300 gpm on annular pressure drop when pumped 14.2 ppg mud on the 16 000 ft slim hole has annular pressure of 4400 psi compared to 640 psi in the conventional well. Because of the narrow annular geometry in SHD, the annular pressure drop is increased. The result showed also a significant increasing in the system pressure loss due to pressure increase in the annulus of slim hole well. The pump pressure loss is the sum of the pressure loss at the surface + pressure lost through the pipe, annulus and the bit.

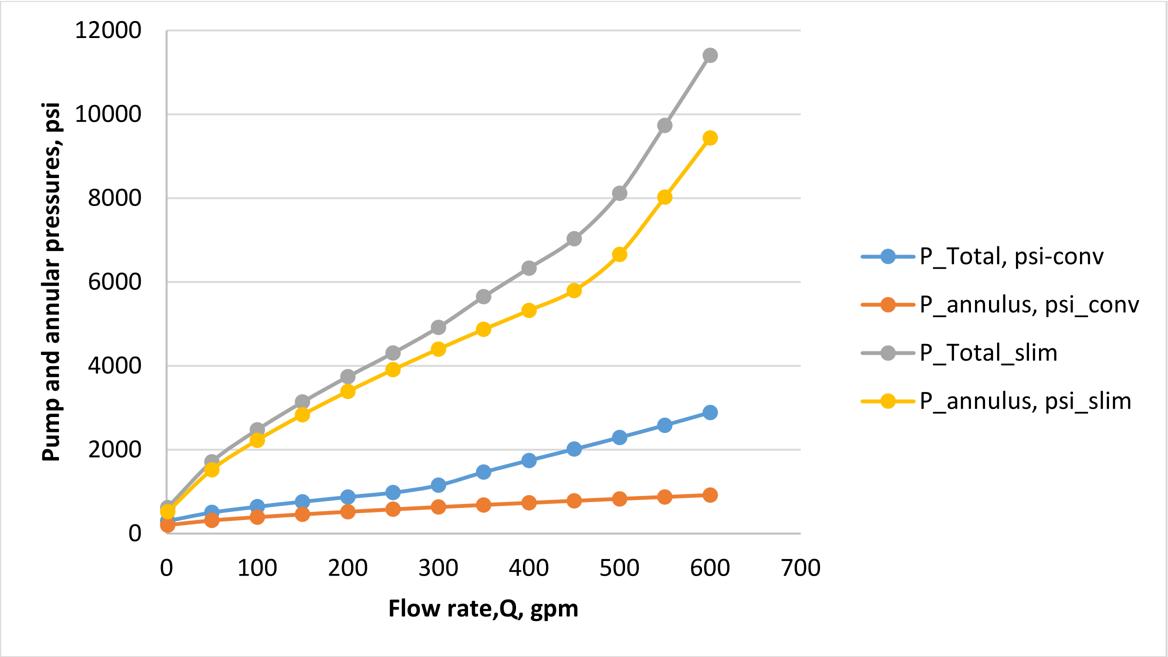


Figure 5.2: *Total pressure Loss vs Flowrate comparison of slim hole and conventional well*

5.1.2.2 Pressure and ECD analysis with viscous and less viscous fluid systems

Aadnøy (2010) proposed a design methodology called ``the median-line principle''. According to the author the mud weight is a key parameter in drilling operation and the difference between success and failure is nearly always tied to the mud program. This means that too low mud may cause in collapse and fill problems, while too high a mud weight may result in mud losses or differential sticking. To minimize the borehole problems, the mud weight should be maintained close to the level of the in situ stresses. The author also states that the two most drilling problems are stuck pipe and circulation losses and may take 10-20% of the total well time which can be high cost to the drilling operation.

Figure 5.3: illustrates typical mud weight selections. The median line mud weight is beneficial and will provide a common optimum for many key elements that influence to the success of a drilling operation.

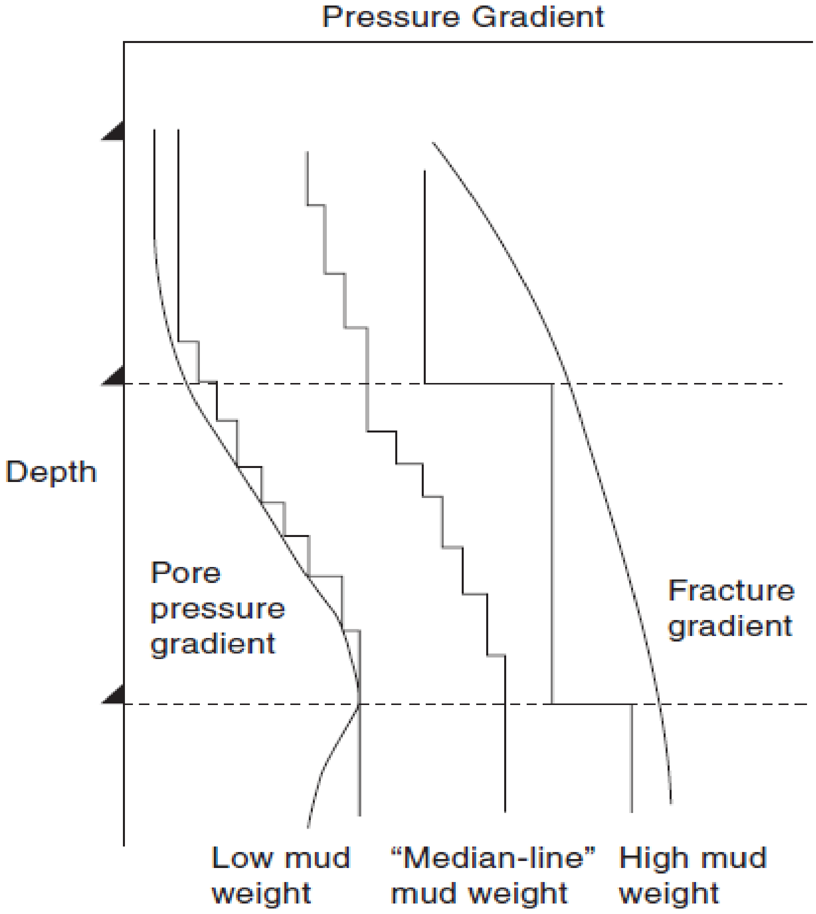


Figure 5.3: *Optimal mud weight selection [40]*

Therefore, in this simulation approaches the relationship between the ECD and the fracture gradient in order to minimize the risk of differential sticking or lost circulation. The equivalent circulating density is plotted versus fracture line to illustrate the required mud density to assess well hole stability to achieve a successful drilling operation

This section presents the behaviors of pressure and ECD in slim and conventional. For this simulation both the viscous and the less viscous fluids shown in table 5.2 were used. The less viscous is 10% reduction of the viscous. This shows that the density of the viscous and the less viscous are 14.1ppg and 11.3 ppg, respectively. In this simulation

In figure 5.4 represents Equivalent Circulating Density in annulus versus fracture gradient with effect of reduced mud weight from 14.1 to 11.3 ppg. The blue curve represents the fracture gradient point. The red curve represents the conventional ECD with mud weight equal to 14.1 ppg , the grey curve represents the slim ECD when the mud density equals to 14.1 and the orange curve represents the slim ECD when the mud weight is 11.3. We observe that (grey) curve crosses the fracture line and may result to mud losses or pipe sticking when the mud weight equals to 14.1 ppg or because of the reduced annular clearance, While the (orange) curve indicates that it is safe which lies under the fracture line when the mud weight is reduced to 11.3 ppg. Higher ECD may affect drilling parameters such as mud flow rate.

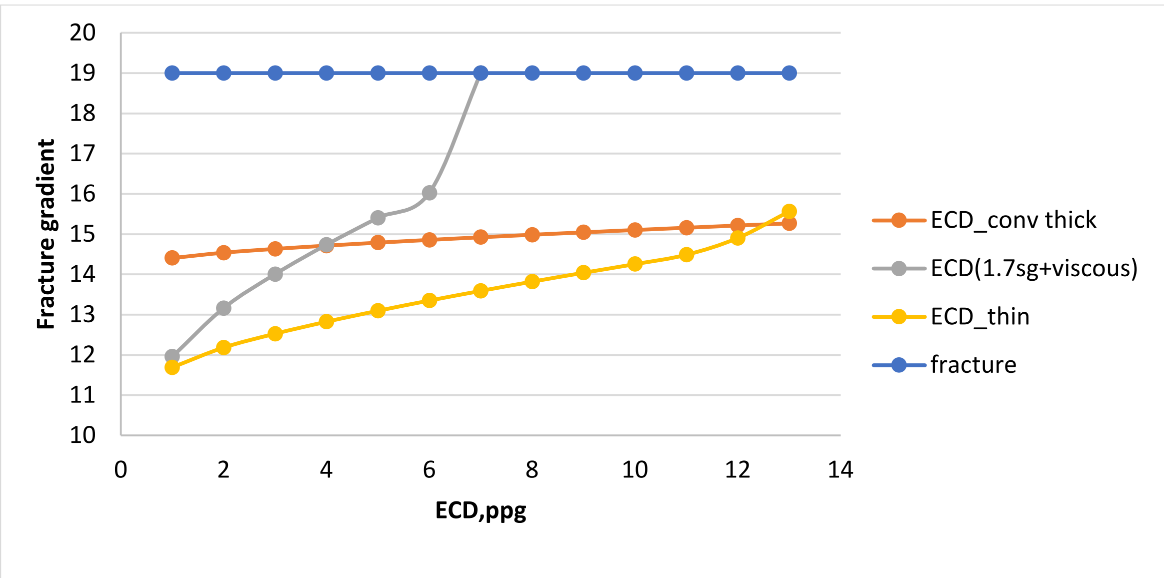


Figure 5.4: *Equivalent Circulating Density (PPG) vs. Fracture gradient with varying Mud Weight*

Figure 5.5: shows the relationship between flow rate (Q) and pressure drop. With pressure in the annulus and pump pressure is applied while the flow rate from one to the maximum of 600 gpm is used. The pressure losses is calculated for each flow rate. The following figure illustrates how the mud weight substantially affect the annular pressure drop when reduced. As it can be seen on the figure, after the reduction of mud weight, the total pressure and the pressure in the annulus in the slim well is decreased compared to Figure 5.2. To minimize the potential threat to hole stability and well control, it is important to use the desired mud weight in one hand and flow rate on the other hand. In addition, it is essential to select accurate model that predicts the pressure losses in the annulus and ECD. Since the borehole instability is more problematic in Slim hole drilling technique because of the involvement of fluid flow in the reduced annular geometries. , it is essential to select accurate model that predicts the pressure losses in the annulus and ECD. Due to no standard pressure models that has been accepted to analyze the pressure losses in the annulus for slim hole condition, therefore, the model used in this figure is based on the unified hydraulic model.

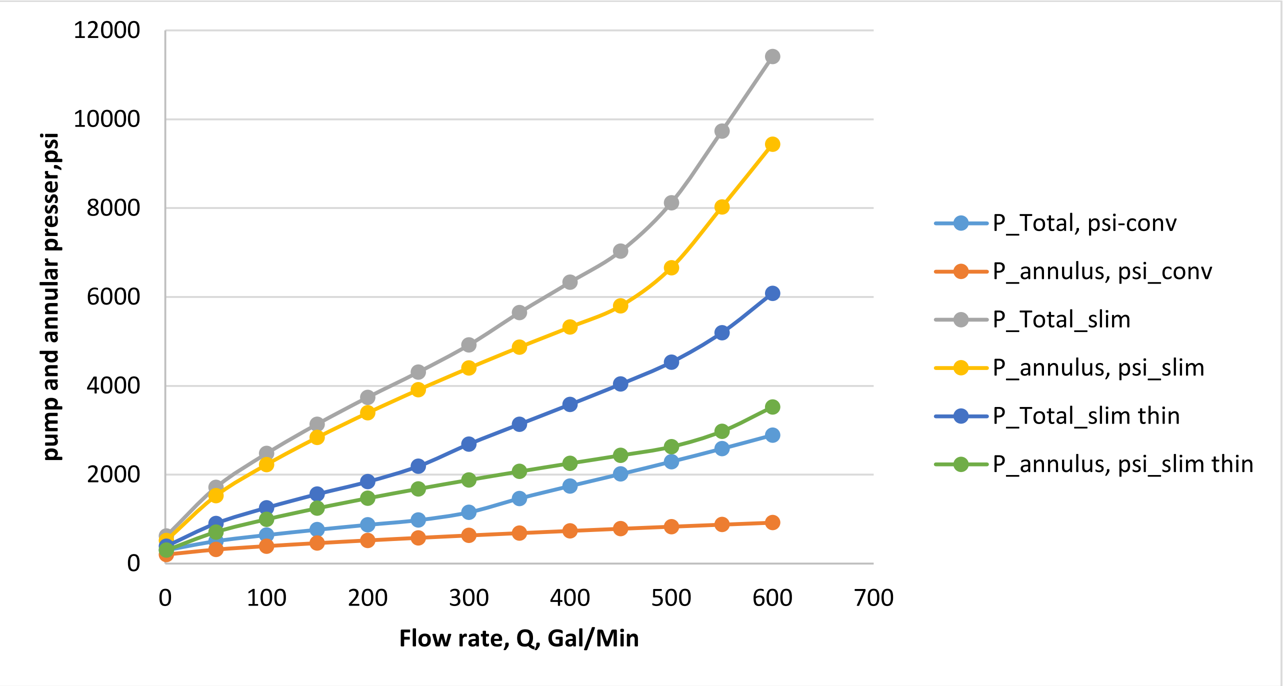


Figure 5.5: *Flow Rate, Q, Gal/min vs Pressure loss, DP, psi*

5.2 Hole Cleaning

During drilling phase, transportation of drilled cuttings is vital factor to be considered for efficient hole cleaning since it is an important topic that remains one of the major concerns to the drilling operation in the oil and gas industry. Removal of drilling cuttings from annulus space and efficient transport of cuttings to the surface is an essential to the drilling operation.
In effective hole cleaning can lead to costly drilling problems such as slow drilling rate, high torque and drag. An excessive cuttings in the annular of the slim hole because of the high flowrate can increase the ECD to cross the fracture gradient and lead to formation fracturing and in the worst case, can cause stuck pipe. These problems can be avoided by understanding the nature and causes of the problem. Therefore, it very crucial to handle this type of situation properly during well planning operation to establish a sufficient hole cleaning.

A good borehole cleaning can be achieved by careful monitoring and properly controlled during the removal of cuttings at the hole bottom and from the bit teeth to the surface. Optimization of cutting transport in the annulus depends on numerous factors such as fluid density, annulus geometry, size of the cuttings, cutting bed-formation, drill pipe rotary speed, drilling rate, hole inclination and fluid rheological properties of the drilling fluid.
Although many studies on hole cleaning has been conducted on conventional drilling by the drilling industry, there is still inadequate studies on cuttings transport in slim hole drilling. In below section, a cutting transport simulation was conducted to evaluate the effect of parameters on bed height and minimum flowrate to transport drilling cuttings through the annular space

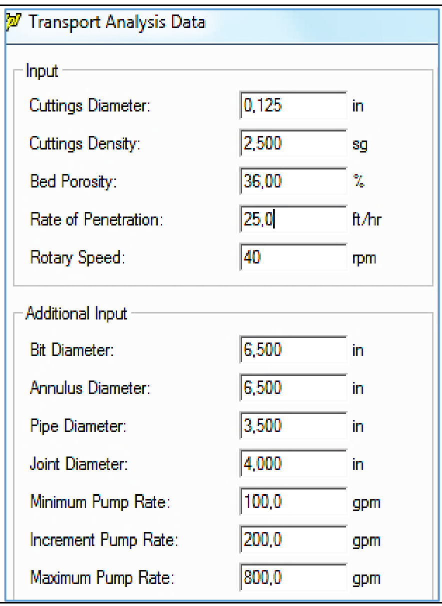
5.2.1 Cutting transport on ultra-deep slim hole-Kuwait-2000ft

The cutting transport simulation was performed on the well geometry discussed earlier in section 4.3. in addition, the behavior of cutting in bed and the effect of flow rate was compared between slim hole and conventional hole.
The well geometry, drilling string data and hole data used in this part can be found in section 4.2.4 in chapter 4.

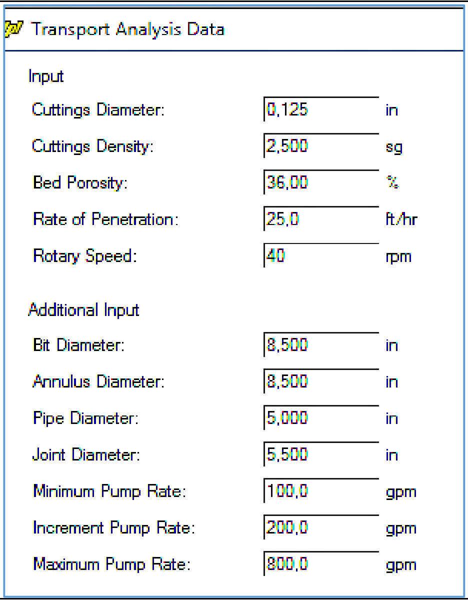
5.2.1.1 Simulation parameters

The purpose of this chapter is to study the hole cleaning issues in slim hole and conventional hole. For the study, we used an industry Landmark/Wellplan software. Figure 5.6: shows the transport parameters used in the cuttings transport phenomenon. It shows also that the drill string for slim well should have an annulus diameter of at least 6.5 in and 3.5 drill pipe down to the BHA for the hole cleaning problem analysis. The simulation was performed using rate of penetration around 25 ft/hr, minimum pump rate for 800 gpm and 40 RPM for the drilling rotation.

Hole cleaning Simulation arrangement for Kuwait-2000ft



Transport parameters for Slim hole



Transport parameters for Conventional hole

Figure 5.6: *Transport parameters used in the cuttings transport phenomenon.*

5.2.1.2 Drilling fluid (Fann)

For this simulation, a higher viscous Oil based mud (OBM) and mud weight of 18.6 ppg (1.86 s.g) was considered. The rheological properties from Fann data 70 used on cutting transport simulation have been adapted from table 5.2.

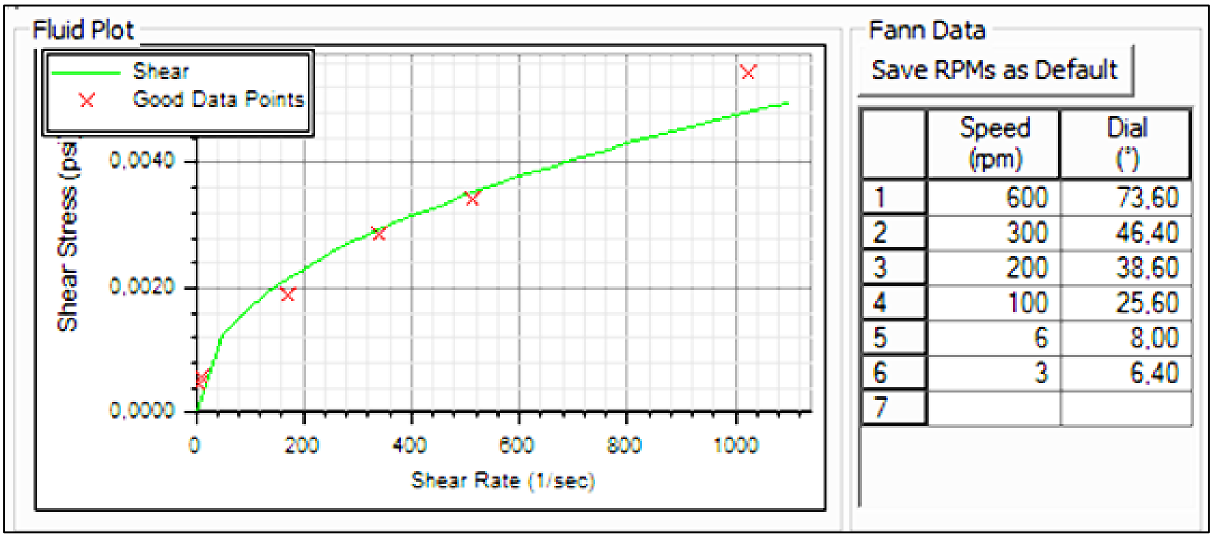


Figure 5.7: *Rheogram (Shear stress vs Shear rate) and Fann data used to characterize the fluid behavior.*

5.2.2: Simulation results

5.2.2.1 Minimum flow rate simulation result

In the experimental well, minimum flow required to transport cutting were simulated and shows in Figure 5.8. The simulation assumed a well from vertical to horizontal well. The objective of this simulation is to analyze the cutting transport phenomenon in geothermal (i.e. typical vertical) and petroleum well (deviated to 90deg.) As can be seen from the vertical well, the slim well requires about 48% less flow rate than the conventional well. Similarly, in horizontal well, the slim hole requires about 46% less flow rate than the conventional well. One of the possible reason among others is that in slim hole the cutting concentration is lower than the conventional.

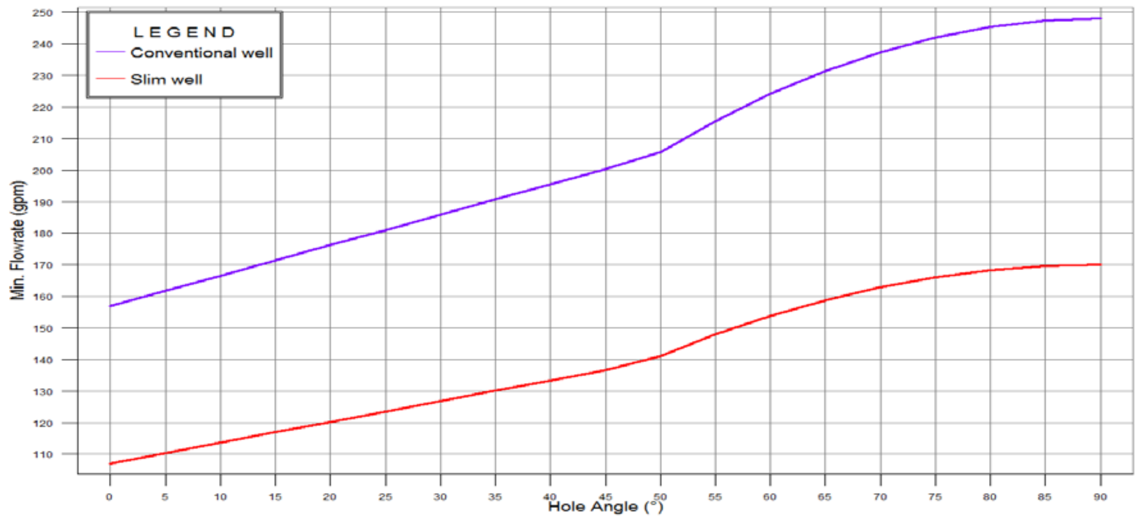


Figure 5.8: *Minimum flow rate vs angle of hole inclination when mud weight of 18.6 ppg is used.*

Hence, the smaller annular cross section area in a slim hole lowers the flow rate needed to achieve the required annular velocity for adequate cuttings removal. In theoretically, bore hole cleaning should not be problem in slim holes but other factors become more important and may dominate. For instance, mud flow rate and annular flow regime (laminar or turbulent) is much more critical in slim-hole well geometry than conventional.

5.2.2.2: Bed height simulation

Poor-hole cleaning causes several drilling related problems. For instance, as mentioned in the introduction part, cutting accumulation in a well increase torque, drag, lower ROP, increase ECD and drill string sticking. Before drilling, it is important to simulation study in order to determine the minimum flow rate to transport and also to compute the ECD so that it will not exceed well fracture gradient. In this section the effect of flowrate on bed height were analyzed in the well geometries. For the study the real well geometry was considered and the well inclination is shown on Figure 5.9. The bed height simulation was performed in the following well inclination.

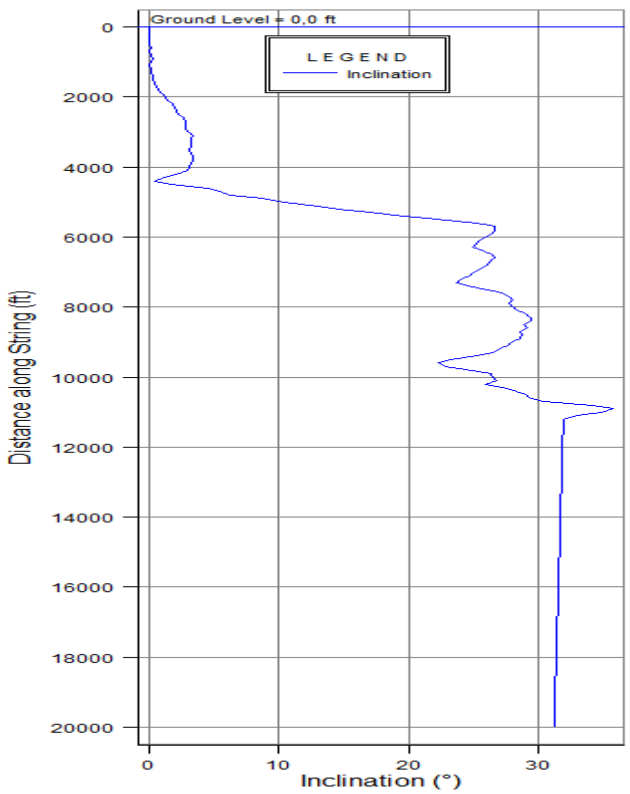


Figure 5.9: *Distance along string vs angle of inclination for the real well geometry.*

Figure 5.10 shows the simulation result for the bed height in slim and conventional hole carried out on well depth of 2000 ft (See table 4.2 and 4.4). From the simulation it was found out that the minimum flow rate required to completely remove from slim and conventional well was

130 and 246gpm, respectively. In order to observe bed height, during simulation we used a 125gpm pump pressure. As shown on figure 5.10, as the inclination angle increases, the bed height for slim hole increases 0 to about 0.30 inch while the conventional hole is around 3.40 inch. In other words, the result from simulation indicates greater cuttings bed is formed in larger holes than slim holes. This is due to the smaller annulus diameter in slim hole which requires lower flow rate to achieve the capability to transport cuttings. As it can be also observed from the figure, the conventional hole needs a higher flow rate (246 gpm) than slim hole in order to increase the lifting capability, or else causes that cuttings to deposit on the inclined section of the wellbore. Many studies have shown that the flow rate is the main factor affecting the cuttings transport performance.

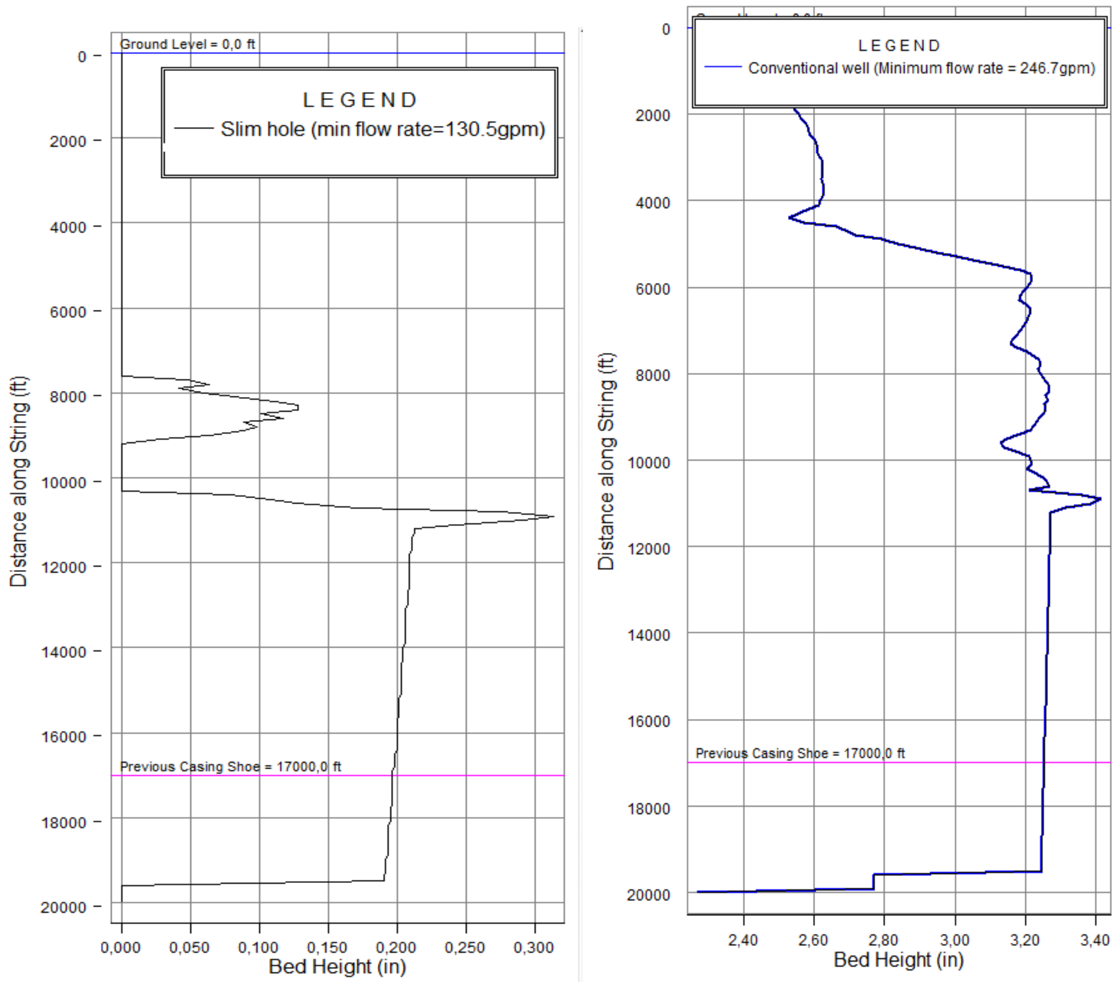


Figure 5.10: *Variation of bed height for slimhole and conventional hole with pump pressure (125gpm)*

5.2.2 Cutting transport deep slim hole-Carter Creek field-16000 ft

In this section, simulation was carried out in order to analyze the factors affecting cuttings transport controlled by many parameters such as effect of drill pipe rotation (RPM), rate of penetration(ROP), bed height and as well as inclination, hole and drill pipe diameter. The purpose for the analysis is to determine if the hole can be cleaned effectively with the applied transport parameter data such as applying by varied flow rate.

5.2.2.1 Simulation arrangement for cuttings transport

The cutting transport simulation was carried out to investigate the parametric and operational sensitivities of slim well compared to conventional well. The simulation arrangement was based on the data set on table 5.2.2.1 given in appendix-B.

During this simulation, the following drilling parameters are kept constant for both optimized slim hole and conventional hole:

- Cuttings Diameter =0.125 (inch)
- Cuttings Density =2.5 (SG)
- Bed Porosity = 36%
- ROP = 25 (ft/hr)
- RPM = 50 rpm
-

In addition, it is been simulated using a flow rate ranging from 200 to 400 gpm. In this part, it is common to use different bit size because of the comparison of the two type of the well that have different geometries. To show how to achieve a cutting transport in slim hole well, it is been considered to use the project on Carter Creek field. Table The bit size and pipe diameter are varying as given on the following table:

Table 5.1: *Transport Data Analysis*

Transport Analysis Data	Conventional Hole	Slim Hole
Bit Diameter (inch)	6.5	8.5
Pipe Diameter (inch)	5	4
Joint Diameter	5.5	4.5

Figure 5.11: the well inclination in which simulation was performed.

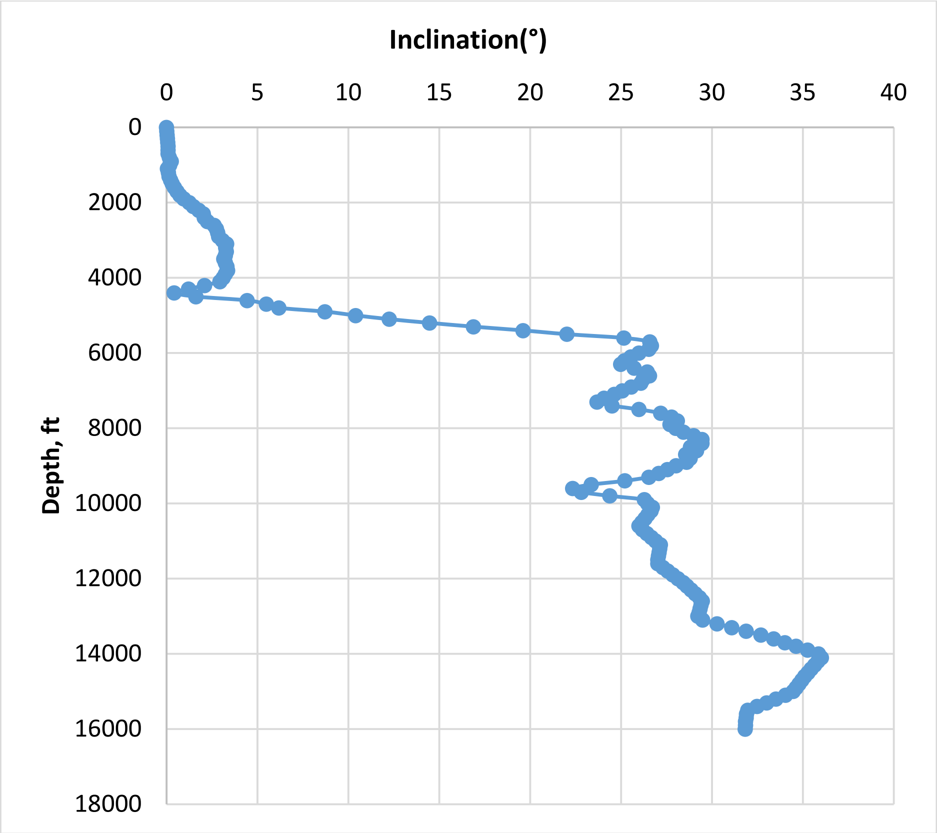


Figure 5.11: *Simulation results in Conventional well (Depth vs angle of inclination)*

Bed height simulation result

In figure 5.12, the blue and orange lines represents for the minimum flow rate required to completely transport cutting out of the slim and the conventional wells, respectively.

In order to create and compare the bed heights in the two wells, we reduced the flow rates by 10% as follows:

a) Slim minim flow rate reduced from 119 to 107ppg
b) Conventional flow rate reduced from 466 to 419 ppg

The result of the simulation are shown on Figure 5.13. As can be observed from the figure below, the bed height for slim optimized well at around 15000 ft increases from 0 inch to approximately 0.5 inch. As well for the conventional bed height began to increase from 0 to 1.5 inch at around 6000 ft.

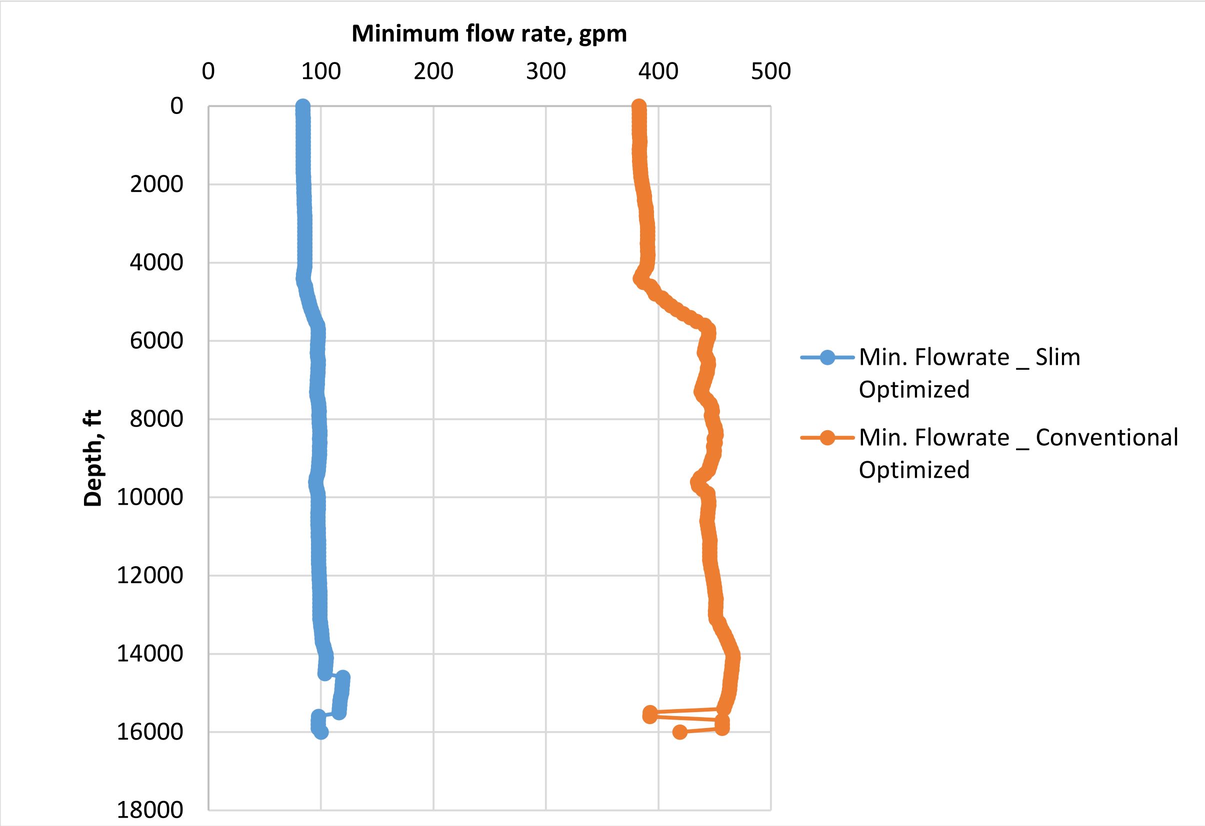


Figure 5.12: Minimum flow rate to transport cutting

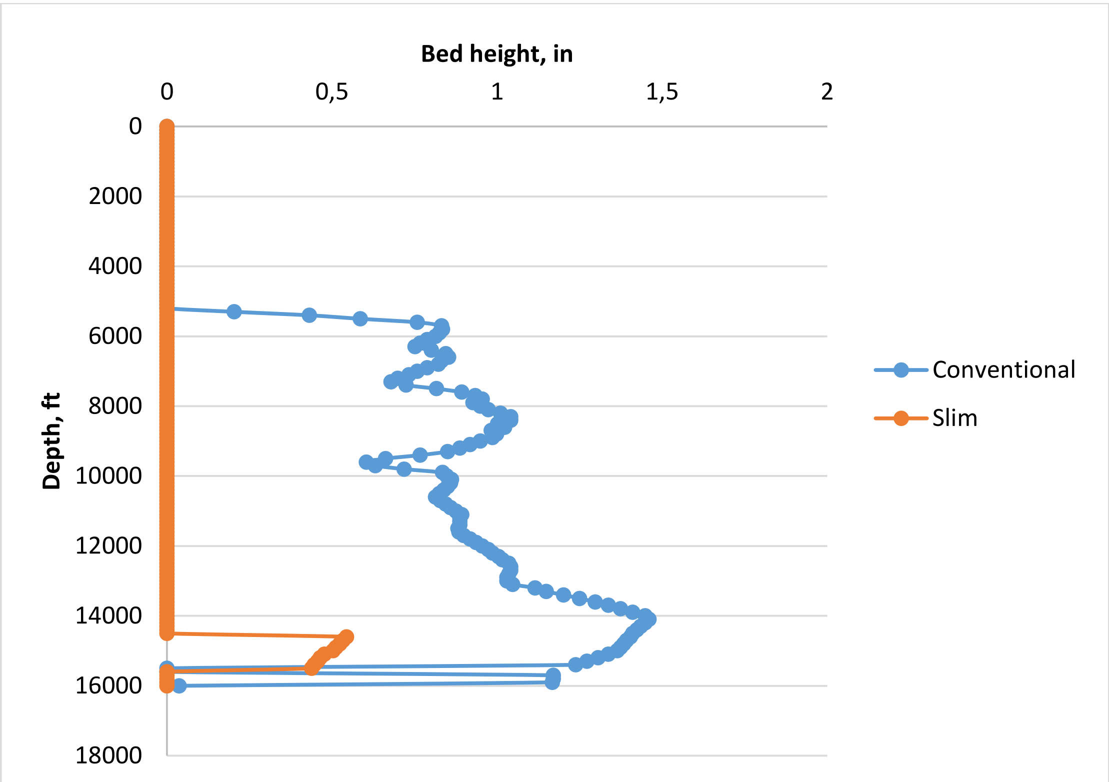


Figure 5.13: Bed height in slim and conventional well

6 Summary and Discussion

In order to qualify the application of slim hole for petroleum and geothermal wells, several simulation studies were carried out. These are torque, drag, stress, hole cleaning and hydraulic performances in the designed system.

6.1 Observation based on simulation

a) Parameters effect

Based on drill string mechanics simulation

Based on both design in Kuwait and Carter field, it is been investigated the critical parameters such as flow rate and friction, which influences drill string mechanics (torque, drag and stresses controlling parameters. In the simulation study, it is found that friction is very crucial when analyzing torque and drag in slim holes. We examined a worst case friction coefficients to ensure if our torque and drag graphs are operating in the safe window when rotating, tripping in/out operations. The results obtained from the simulation study in slim wells shown that:

- Increase in friction factor (FF) will increase the tension value (Drag) during tripping out operation in and vise-versa.
- The torque value increases with lower flow rate during tripping our operation
- It is observed that there is a direct correlation between flow rate and von-mises stresses. The von-mises stresses stays within operational window if applied high flow rate and vice-versa.

Based on hole cleaning and hydraulics simulation

For hole cleaning and hydraulics, flow rate and rheology of drilling fluids are a key parameters, which needs to be examined during slim hole design phase. Based on these, it is possible to qualify the maximum depth one can reach the target.

In the simulation section, it is found that vertical slim wells requires 48% flow rate less than conventional. For horizontal slim wells requires 46% flowrate lower than conventional wells. This simulation result matches with the literature study. As mentioned in the literature study section that drilling with slim wells reduces requires less mud and reduces the amount of cuttings depending on either vertical or inclined well designs. This will greatly minimizes the costs of waste disposal during drilling operation.

In hydraulic simulation, it is been observed higher ECD from drilling slim well with higher mud density (14.3 ppg) crosses the fracture line. As stated in the literature when the mud is being circulated inside the wellbore, the bottomhole pressure increases because of friction forces resulted due to mud moving in the annulus. The ECD from drilling with slim wells increases due to the smaller annulus.

In order to minimize the drilling problems that can cause higher ECD in slim wells such as lost circulation, wellbore stability, kicks, it is important to control ECD by using the desired mud density in one hand and flow rate on other hand. Therefore, after reducing 10% of the mud weight to 11.3 ppg, it is recognizable that is possible to design slim well with less viscous density in order to be within the mud program window.

b) Ultra-deep slim hole well

One of the research question was to answer how long can we drill a slim well. It is been examined a fiction well "worst case scenario" with well length of 24 000 ft based on Kuwait slimhole design. The result obtained from using torque, drag and stresses analysis showed that the drillstring cannot carry the loads. This tells that to drill a well length of 24000 ft to reach the target is one the critical technologies in a slimhole well design. This matches what is mentioned in literature in section 2.6 that a depth can be the key limiting factor when a designing a slim well. Therefore, we selected a well length of 20000 ft to see the benefits coming from the reduction of footage. We started simulating with low grade E and G. it is been found the drillstring passes the tensile limit after shortening the well length. The recognition when unexpected problems occurs, one should face with an immediate remedial action. This can lead to a successful drilling, completion and lower the cost for the project. Therefore, by using S grade solved the problem and recognized as the most suitable grade for the ultra-deep simulation even though it costs higher than E and G grades. Well length reduction and higher grading will push the tripping out/in slimhole design operation to lie within the safe operational window and this generally gives a better ultra-deep slimhole design and well stability.

6.2 Slim hole analysis flow chart

This part present the methodology used to analyze slim hole. As mentioned earlier, three operational issues were considered. Several trial and error simulation were carried out in order to select the right drill string grade and operational parameters, such as ROP, RPM, trip in and out speed, flow rate. Figure 6.1 illustrates the analysis flow chart

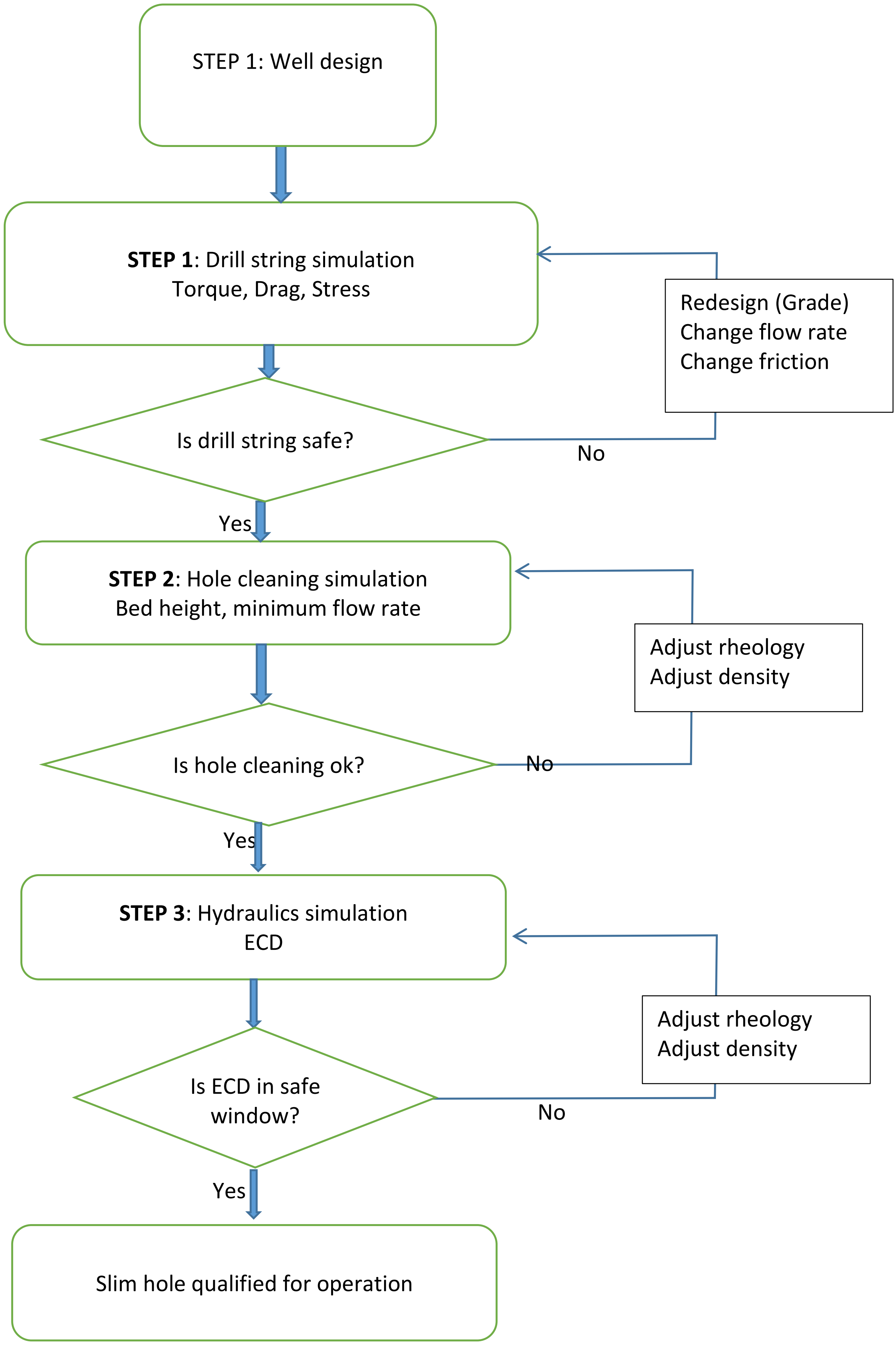


Figure 6.1: Slim hole analysis flow chart

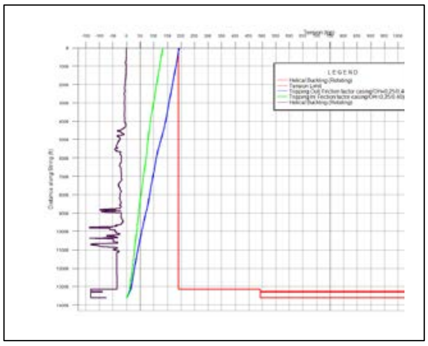
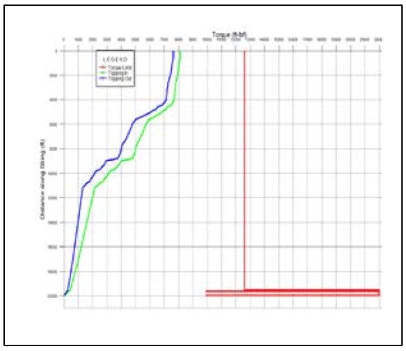
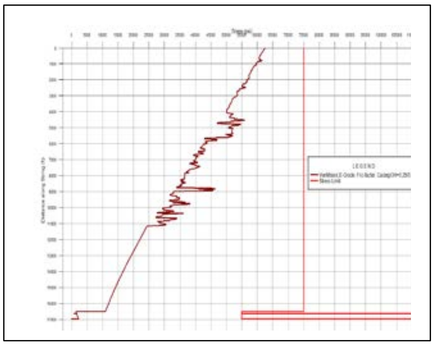
STEP 1: Well design:

The well design consists of

a) Hole section (Open hole + Casing+ Friction coefficient+Flow rate)
b) Drill string desing (Drill pipe + BHA)
c) Well path (Survey, inclination, azimuth, and MD)
d) Drilling fluid (Rhelogy and density)
e) Geothermal gradient (Surface temperature and temperature gradient)
f) Pore pressure
g) Fracture pressure

After building the simulation, the torque, drag and stress simulation will be performed. We determine if the torque, drag and stresses in the drill string exceeds the tensile limit or buckling limit. If the considered system qualified, proceed step two. Otherwise, we need go back and redesign the strings and change the drilling fluid flow rate and change the friction coefficient, which can be controlled by the Oil based mud system. Repeat simulation until the operation be within the safe allowable working window.

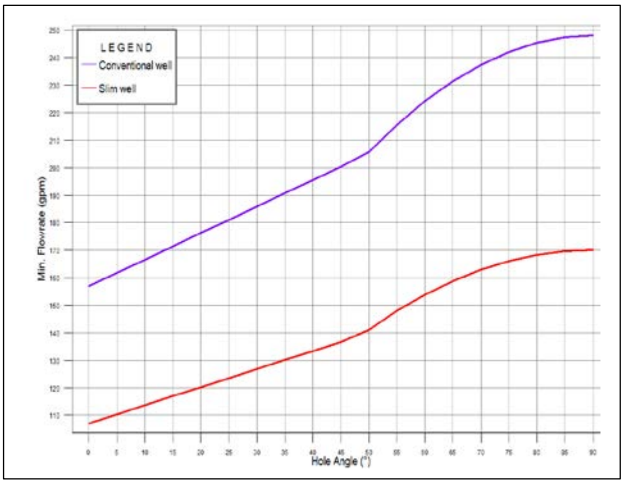
As illustration:

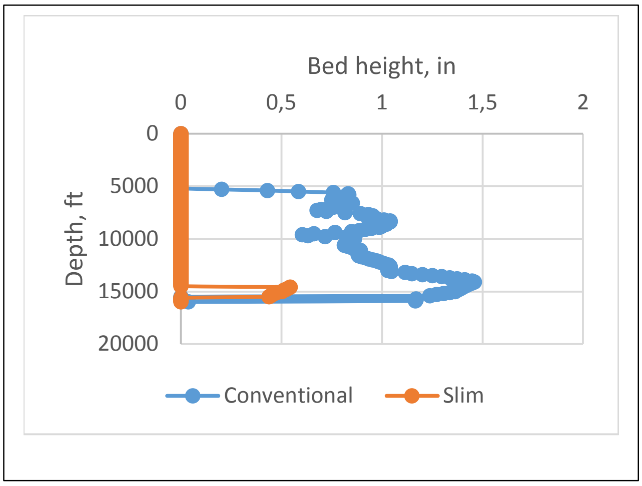




STEP 2: Hole cleaning

Use the transport analysis data available in wellplan to fill up with the required pumprate, rop, rpm, bit diameter, drillpipe diameter, cuttings density and cuttings diameter. If it is achievable with this data's, proceed to the next step. If it is not achievable, consider reducing the drilling fluid density and adjust rheology properties. If still is not, continue increasing the pumprate until an achievable minimum flow rate and bed height for slim well design is obtained.

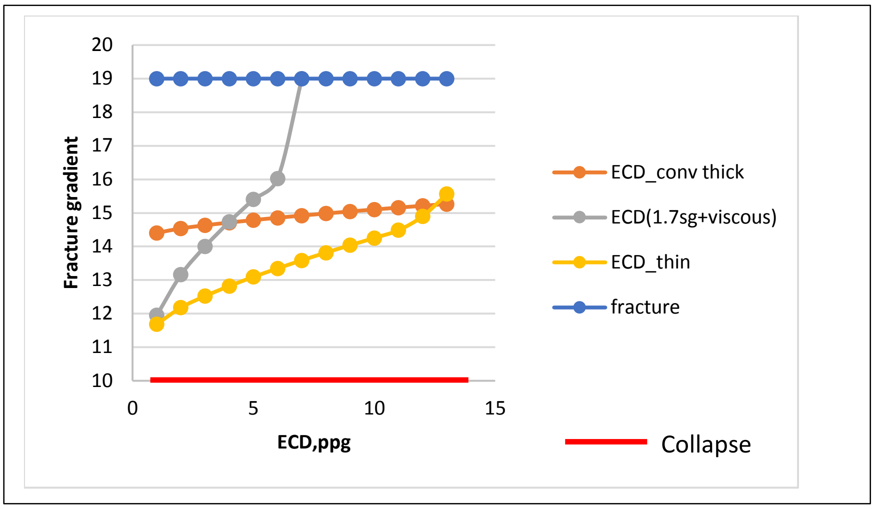
As illustration.





STEP 3: Hydraulic simulation

Use the hydraulic module (Unified) to perform the fracture gradient plots. Compare the results obtained from the simulation. Check if the ECD is below the fracture gradient. If it is determined to be true, proceed to the next step. If it is not, go back to adjust the rheology and density by reducing the mud weight and considering to change the flow rate as required the ECD to remain within the fracture gradient window. Then proceed to the next step if the ECD. First we simulated with higher mud density (14.1 ppg). As seen in the illustration, the grey curve crosses the fracture. Therefore, it is been adjusted the rheology with less vicous mud density (11.3 ppg). This showed that ECD from slim wells can be managed with less viscosu and the right flowrate.



7 Conclusions

In this thesis, several simulation scenarios were generated and tested with three important operational aspects in order to qualify for the application of slim hole design for petroleum and geothermal wells. These are drill string mechanics (Torque, drag, and stress in string), hole cleaning and hydraulics performance. From the overall simulation study, this thesis comes to the conclusion that:

a) For shallow well (13000ft), it is possible to drill with the low grade (E-75).

b) For deep well (16000ft), it is possible to drill with a combination of high (G-95) a low grade (E-75). This design is cost effective and operationally feasible in terms of hydraulics, drill string mechanics and hole cleaning issues

c) For ultra-deep well (20000ft), it is possible to drill with a higher grade drill string namely S-135.

d) Based on the overall simulation results, it is shown that the cutting transport efficiency in slim hole is better than the conventional showing that lower flow rate was able to completely clean up the bed height. The analysis shows both in vertical and horizontal well. This shows the application of slim hole in geothermal and in petroleum wells.in the vertical well, the slim well requires about 48% less flowrate than the conventional. Similarly, in horizontal well, the slim hole requires around 46%.

e) From the simulation study, it was investigated that friction coefficient is very crucial parameter for the torque and drag operation. This can be controlled by using oil based mud and good hole cleaning measures

f) For safe operation, the ECD should be within the operational window. From hydraulics simulation study it was found out that to maintain ECD one can design the appropriate density and rheology during design phase. From the consider simulation arrangement, the simulation results shows less viscous and less density fluid system manage ECD in slim hole provided that using the right flow rate.

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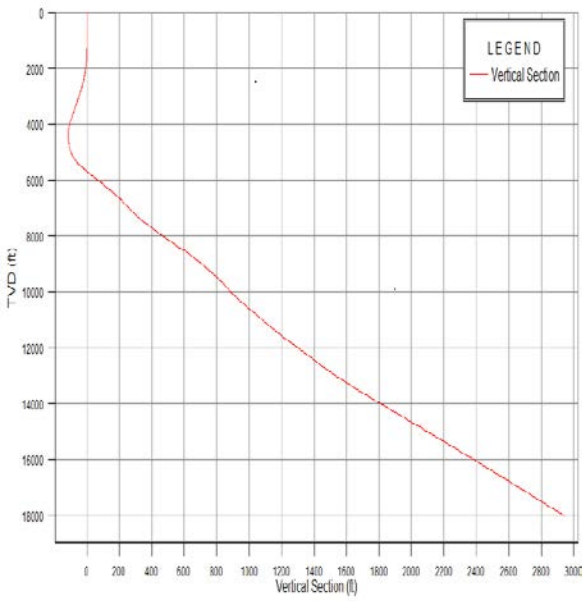
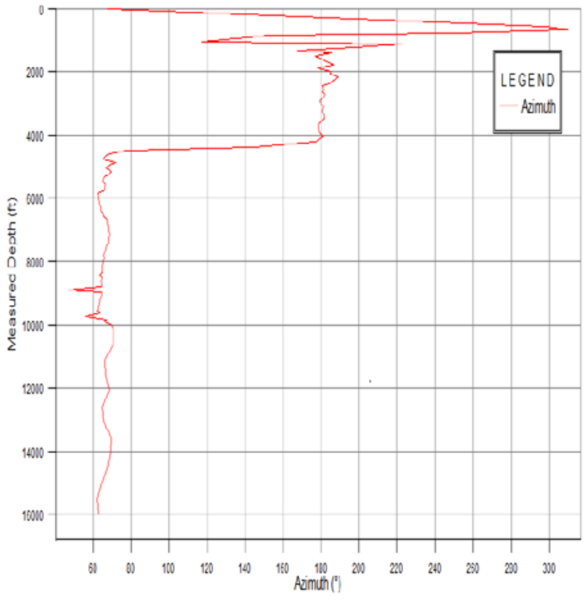
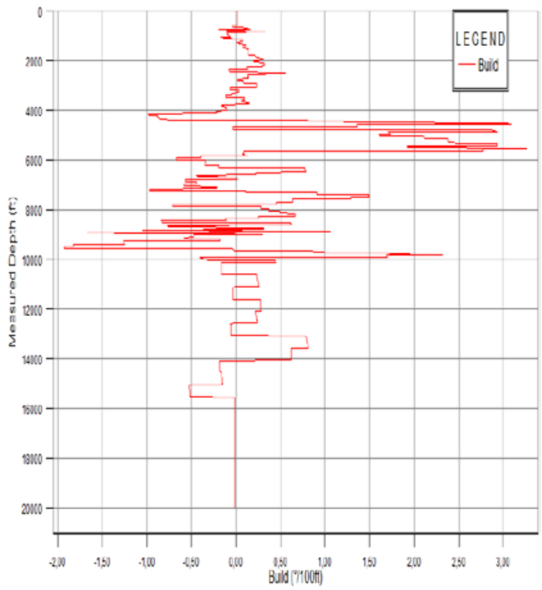
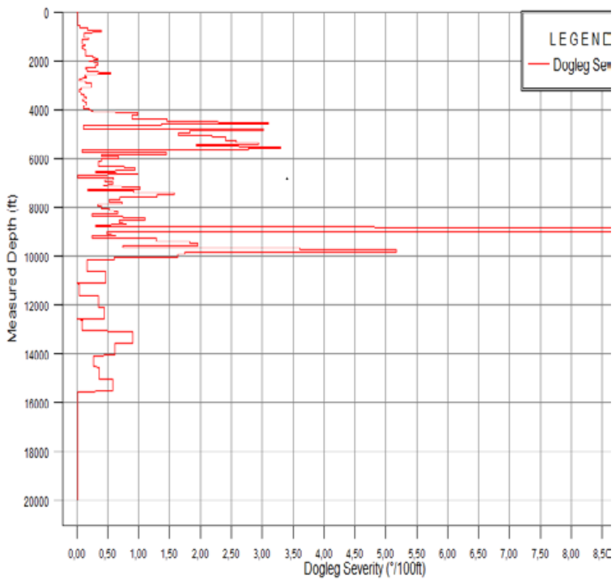
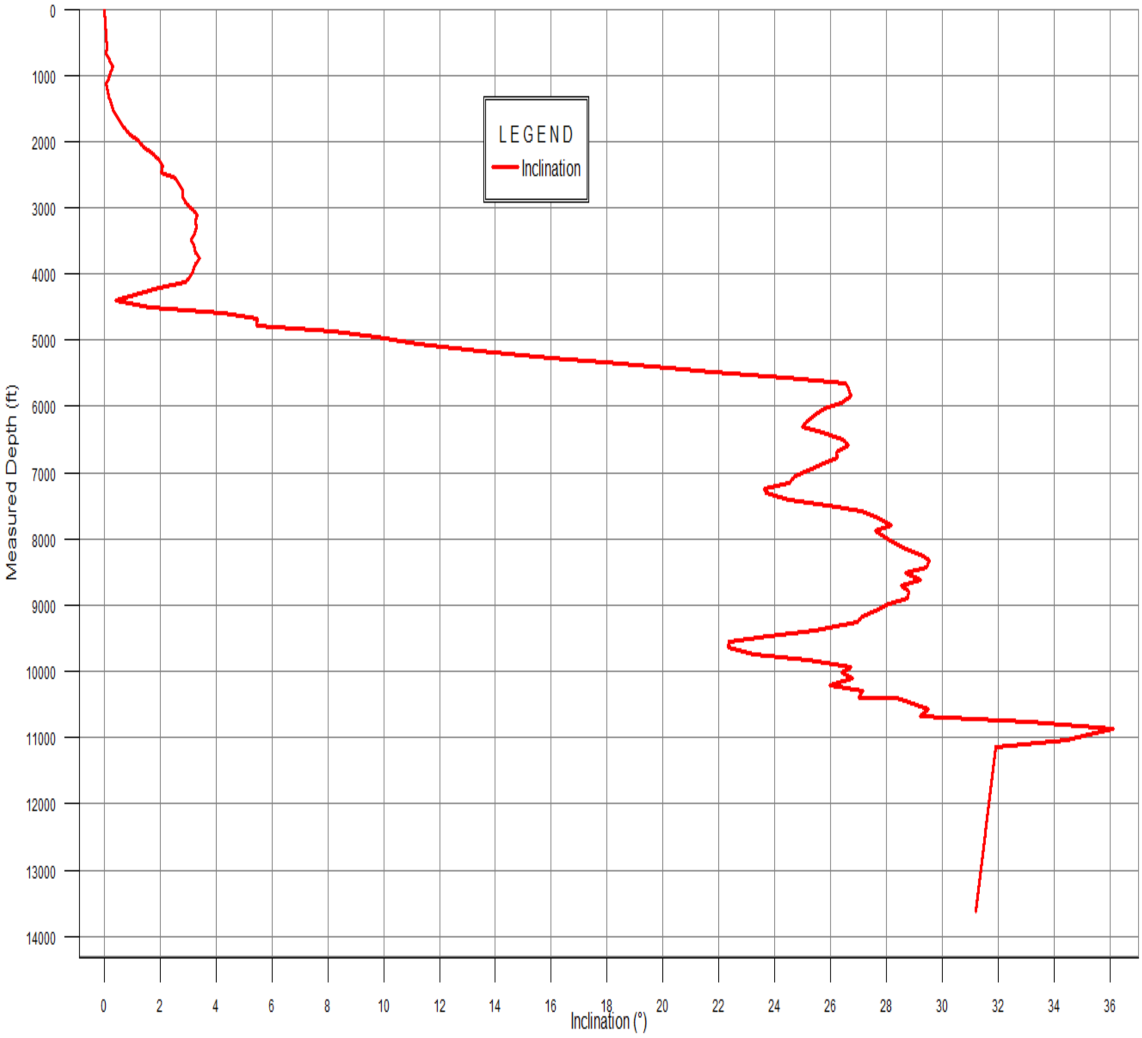
Appendix A: Well Trajectory


LEGEND
Vertical Section
TVD (ft)
Vertical Section (ft)


LEGEND
Azimuth
Measured Depth (ft)
Azimuth (°)


LEGEND
Build
Measured Depth (ft)
Build (°/100ft)


LEGEND
Measured Depth (ft)
Dogleg Severity (°/100ft)


LEGEND
Inclination
Measured Depth (ft)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
Inclination (°)

Appendix B: Cutting transport data

Table 5.2.2.1 and 5.2.2.1 shows the simulation drill string and BHA data used .The simulation arrangement generated in this section has been adapted on Carter- creek field, reproduced hereunder.

Hole Section (Casing + Open Hole)

Hole Section Depth (MD): 16000,0 ft ☐ Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	14500,0	14500,00	6,250	6,413	6,538	0,25	0,0379	7 in, 17 ppf, H-40,
2	Open Hole	16000,0	1500,00	6,250		6,555	0,30	0,0417	

Table 5.2.2.1: Hole data for optimized slim solution (Casing +Open Hole)

Drill string data (Drill pipe + BHE)

String (MD): 16000,0 ft Specify: Top to Bottom Import String Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	6008,00	6008,0	4,000	3,240	17,17	Drill Pipe 4 in, 15.70 ppf, G, H90, P
2	Drill Pipe	9500,50	15508,5	4,000	3,240	17,07	Drill Pipe 4 in, 15.70 ppf, E, H90, P
3	Heavy Weight	120,00	15628,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
4	Jar	32,00	15660,5	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
5	Heavy Weight	305,00	15965,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
6	Sub	3,00	15968,5	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
7	MWD	22,50	15991,0	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
8	Stabilizer	5,00	15996,0	3,250	1,500	22,22	Integral Blade Stabilizer 4 1/8" FG, 3 1/4x1 1/2 in
9	Sub	3,00	15999,0	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2x1 1/2 in
10	Bit	1,00	16000,0	5,875		33,00	Tri-Cone Bit, 3x16, 0,589 in²

Table 5.4.2: String section for 9500 ft and 6000 ft drill pipe length

Well Schematic for Conventional well

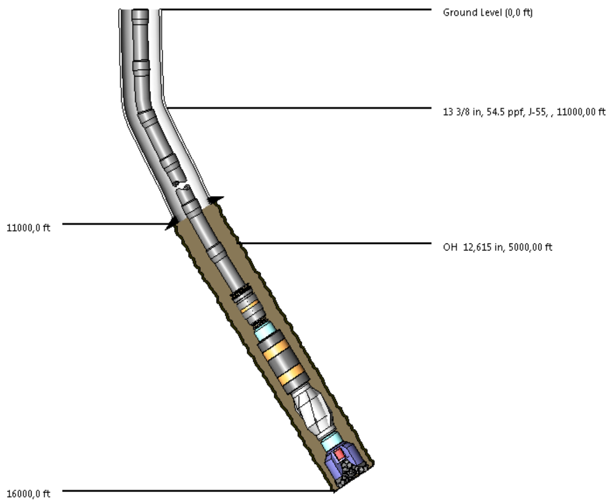
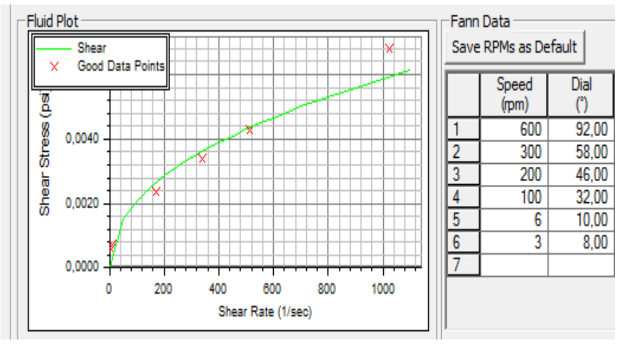
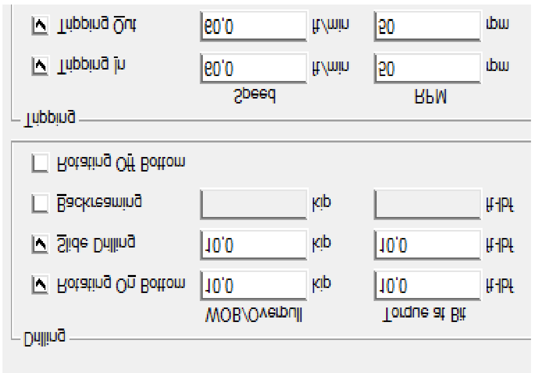
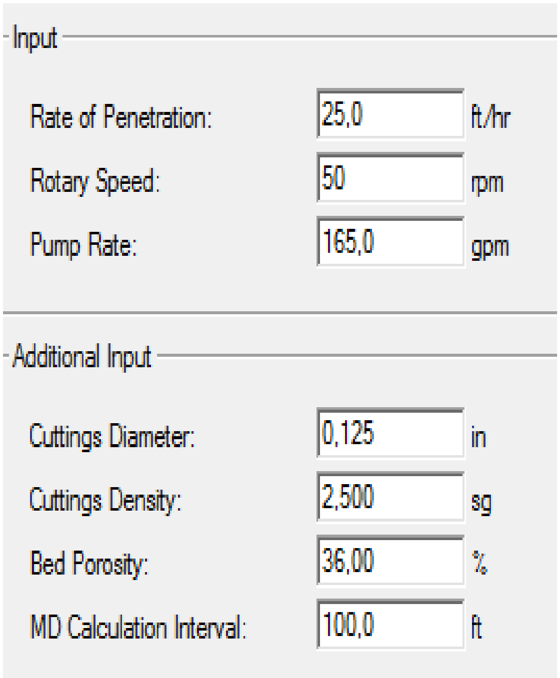


Figure 5.4.1: Drill pipe representation

5.4.4 Drilling fluid and transport analysis Data







Cuttings Transport Parametric

Figure 5.4.4 displays parametric study of a conventional hole (green line) and slim hole (blue line). The ROP value equals to 25 ft/hr (7.62 m/h) was maintained constant in both situation. In this simulation, the result shows that at inclination angle of 35° degrees is required minimum flow rate equal to 120 gpm (454 l/min) for the blue curve and 200 gpm (757 l/min) for the green curve. At inclination of 90° degrees, this corresponds to a minimum flow rate that equals to

175 gpm (662 l/min) and 285 gpm (1079 l/min). Therefore, the figure demonstrates that higher flow rate is required for conventional well than slim well for an efficient hole cleaning.

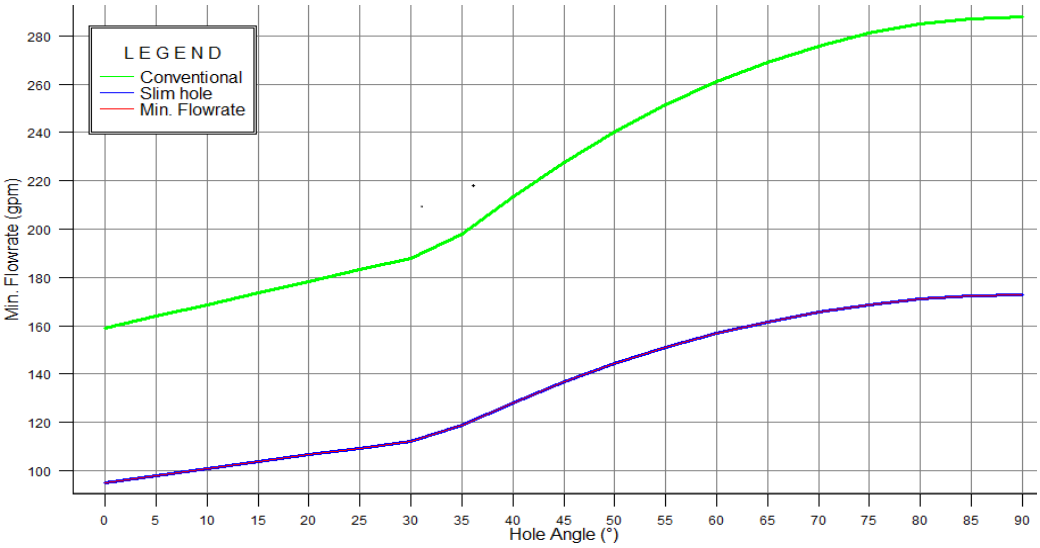
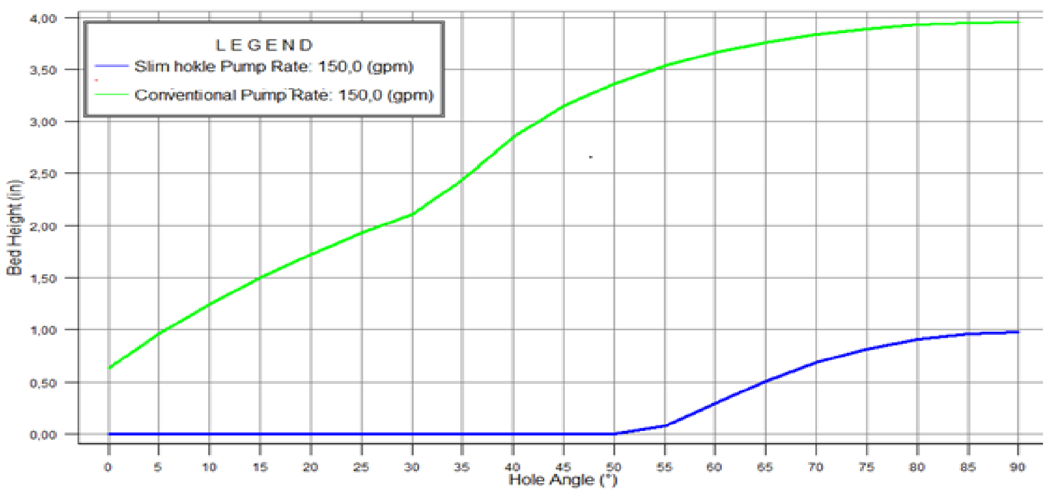


Figure 5.4.5 : Min. Flow rate vs angle of angle of inclination at ROP= 25 ft/hr

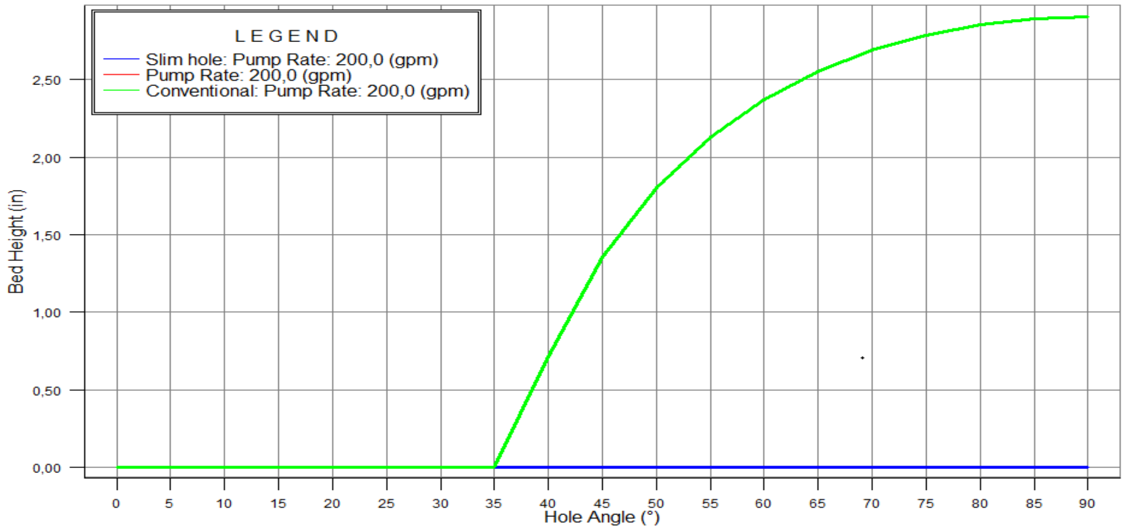
Effect of flow rate on bed height

The simulation results shown on the following figure demonstrates the effect of pump rate (200 gpm) on cuttings bed deposition. The operational parameters used in this simulation are kept constant as presented in the previous section. In figure 5.45, a flow rate value equal to 200 gpm was used to



5.4.5: Effect on flow rate regards to cutting bed deposition at Pump Rate= 150 gpm

For Pump rate at 200 gpm



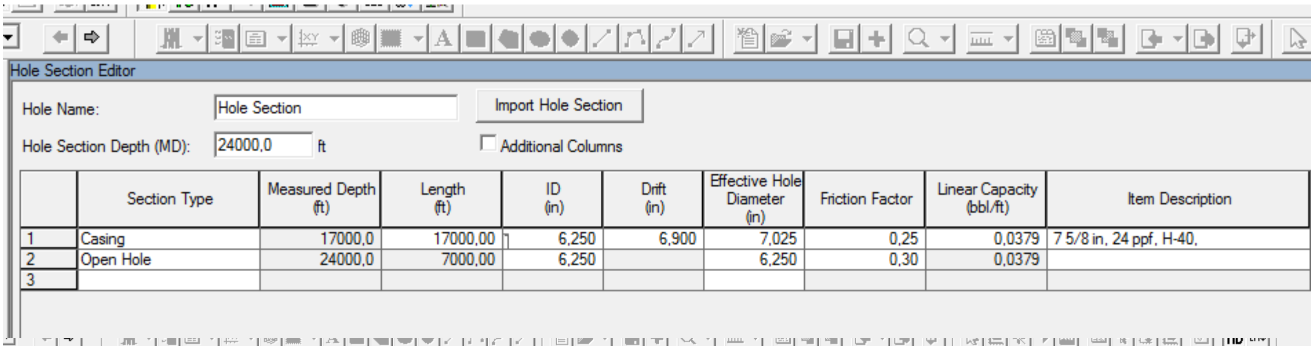
5.4.6: Effect of flow rate = 200 gpm on the bed height

The second observation In figure 5.4.6 indicates that increasing the flow rate to 200 gpm is capable of cleaning the cuttings in the well bore for the slim as the angle of inclination increases compared to the larger size hole. The green curve illustrates that at inclination angle

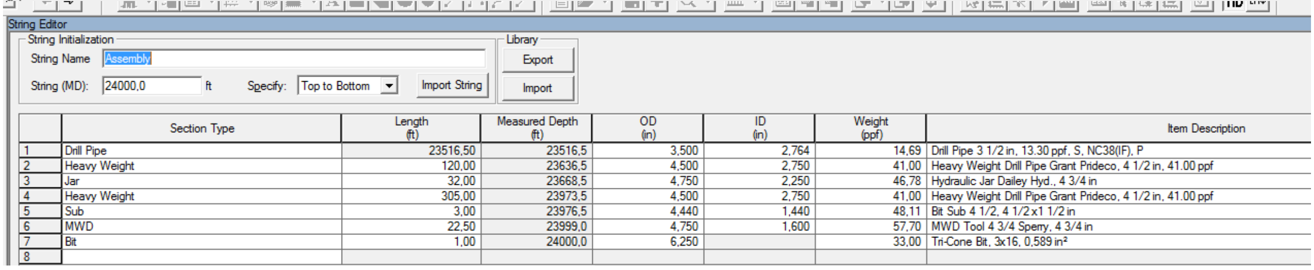
Appendix C: Ultra –deep slim well & Conventional well simulation

C-1:- 24000ft long slim hole-Problem

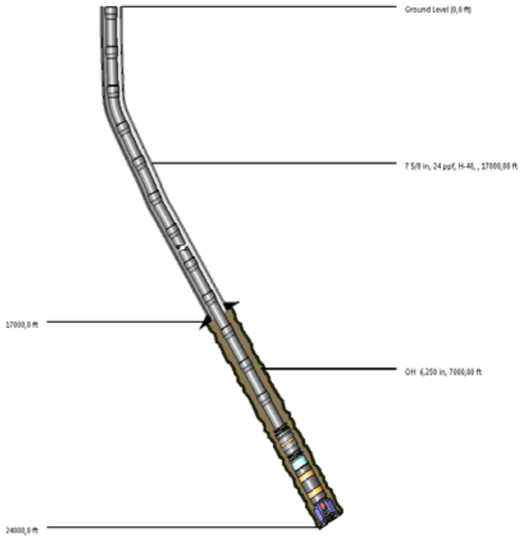
In below section, torque and drag analysis for ultra -deep well will be performed. It was assumed to drill a well to total depth at 24000 ft. In order to have accurate assessment for the forces and stresses affecting in the drill string, we need to analyze the torque, drag and stresses during the drilling operation.

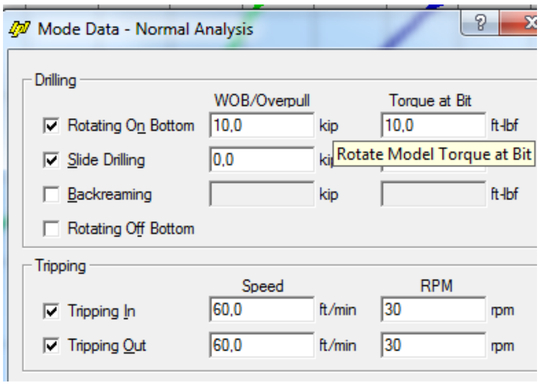


	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	17000,0	17000,00	6,250	6,900	7,025	0,25	0,0379	7 5/8 in, 24 ppf, H-40,
2	Open Hole	24000,0	7000,00	6,250		6,250	0,30	0,0379	
3									

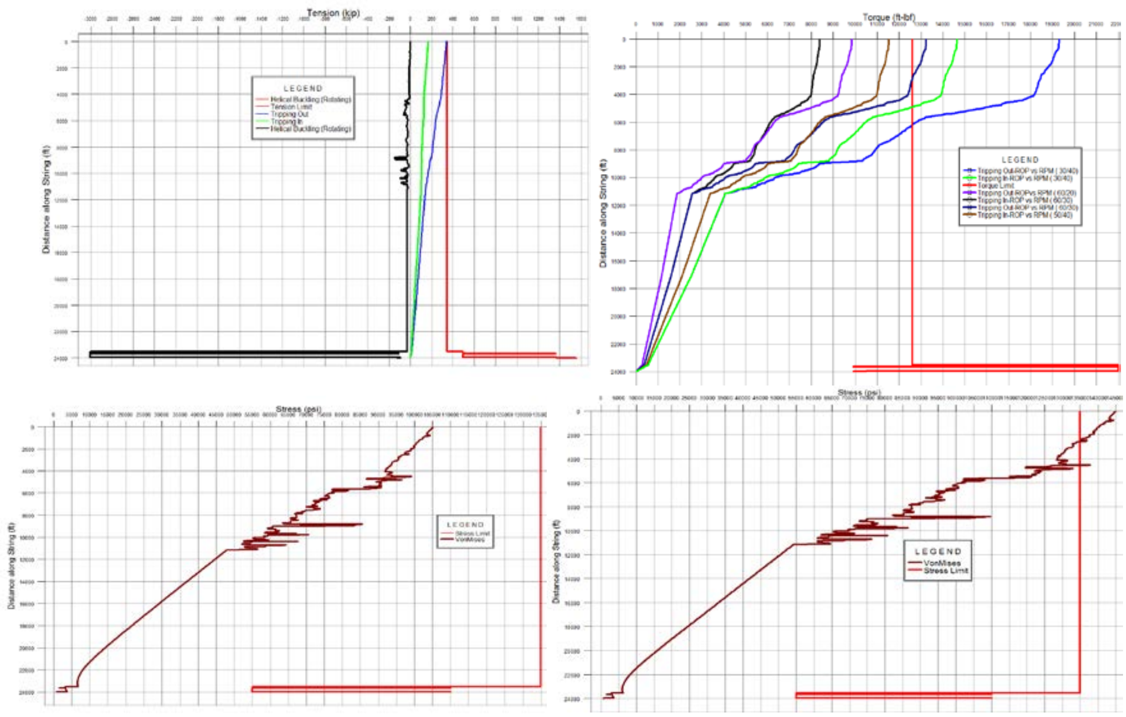


	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	23516,50	23516,5	3,500	2,764	14,69	Drill Pipe 3 1/2 in, 13.30 ppf, S, NC38(IF), P
2	Heavy Weight	120,00	23636,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
3	Jar	32,00	23668,5	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
4	Heavy Weight	305,00	23973,5	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
5	Sub	3,00	23976,5	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2 x1 1/2 in
6	MWD	22,50	23999,0	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
7	Bit	1,00	24000,0	6,250		33,00	Tri-Cone Bit, 3x16, 0,589 in²
8							





The follow shows the results of torque obtained for a well that has been extended to target depth of 24000ft. As can be seen on the tension graph, tripping out curve crosses the operating limit.



C-2: 17000ft long conventional hole-Solution based on Kuwait well

The problem presented in appendix-2 was solved by using a higher grade on the top section of the drill string. The results are shown on Figure YY1

Hole Section Editor

Hole Name: Wellbore Name | Import Hole Section

Hole Section Depth (MD): 17000,0 ft | Additional Columns

	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	16000,0	16000,00	6,250	6,413	7,538	0,20	0,0379	7 in, 17 ppf, H-40,
2	Open Hole	17000,0	1000,00	6,250		6,480	0,30	0,0410	
3									

String Editor

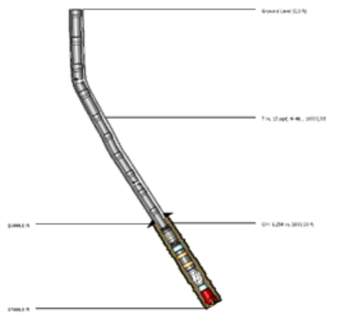
String Initialization

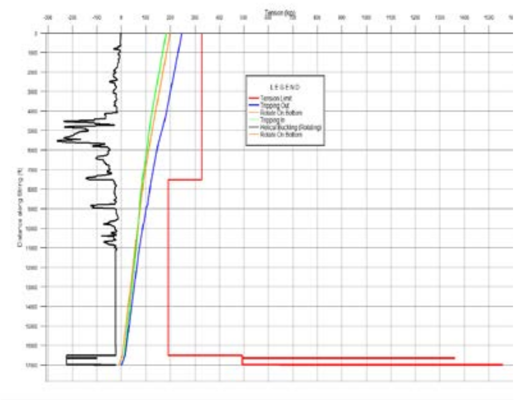
String Name: Assembly

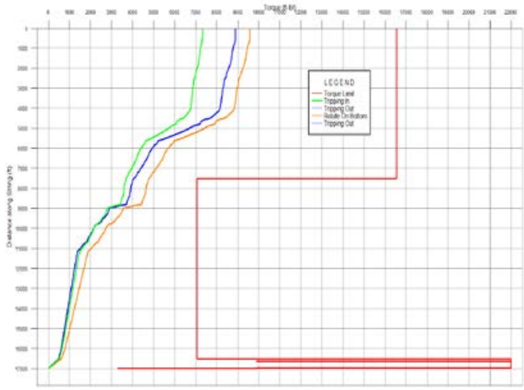
String (MD): 17000.0 ft | Specify: Top to Bottom | Import String

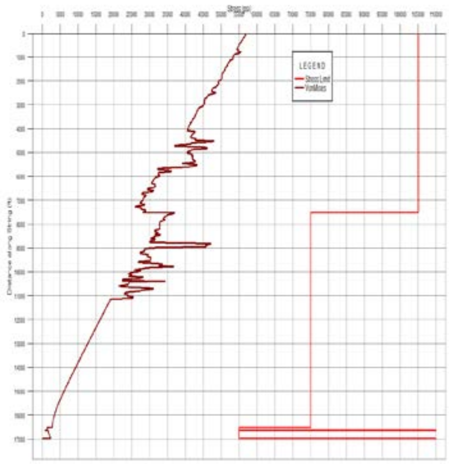
Library: Export | Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	7508,78	7508,8	4,500	3,826	18,88	Drill Pipe 4 1/2 in, 16.60 ppf, G, NC46(XH), P
2	Drill Pipe	9000,00	16508,8	3,500	2,764	14,41	Drill Pipe 3 1/2 in, 13.30 ppf, E, H90, P
3	Heavy Weight	120,00	16628,8	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
4	Jar	32,00	16660,8	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
5	Heavy Weight	305,00	16965,8	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
6	Sub	3,00	16968,8	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2 x1 1/2 in
7	MWD	22,50	16991,3	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
8	Stabilizer	5,00	16996,3	3,250	1,500	22,22	Integral Blade Stabilizer 4 1/8" FG, 3 1/4 x1 1/2 in
9	Sub	3,00	16999,3	3,480	1,440	26,72	Bit Sub 3 1/2, 3 1/2 x1 1/2 in
10	Bit	0,72	17000,0	5,875		85,00	Polycrystalline Diamond Bit, 0,400 in²
11							



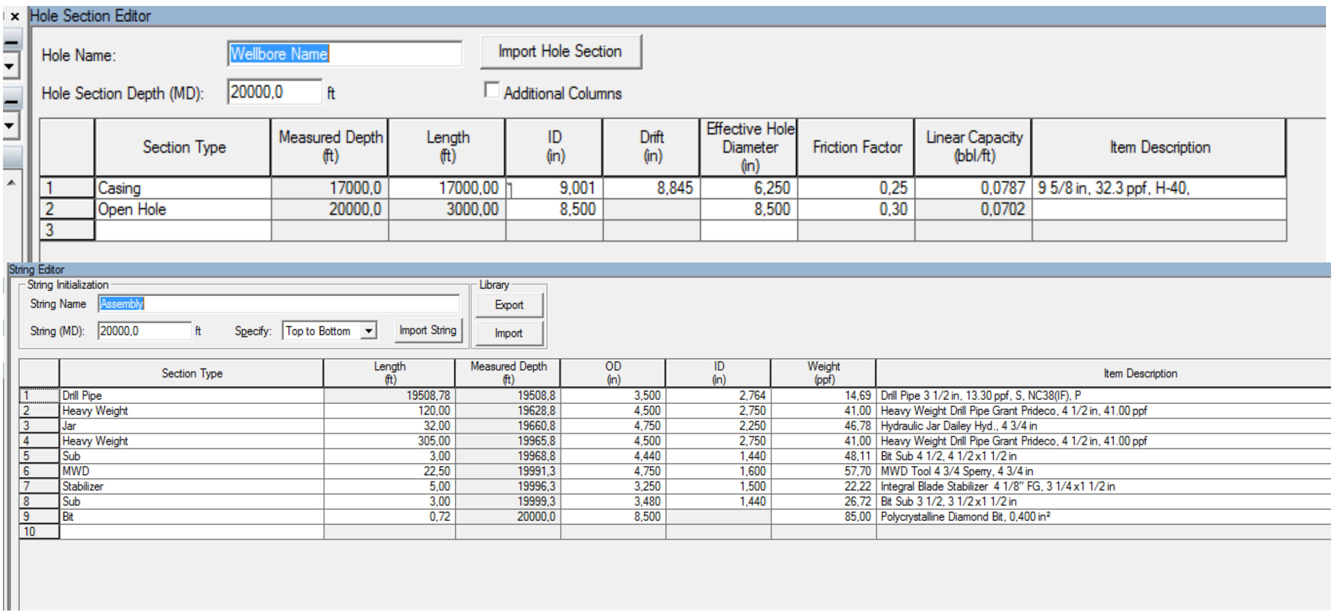






As results obtained from the simulation, both situations indicates that the von Misses stress does not exceeding the yield point. Therefore, the operation is a safe.

C-3:-20000ft long conventional hole-Solution



Hole Section Editor

Hole Name: Wellbore Name | Import Hole Section

Hole Section Depth (MD): 20000,0 ft | Additional Columns

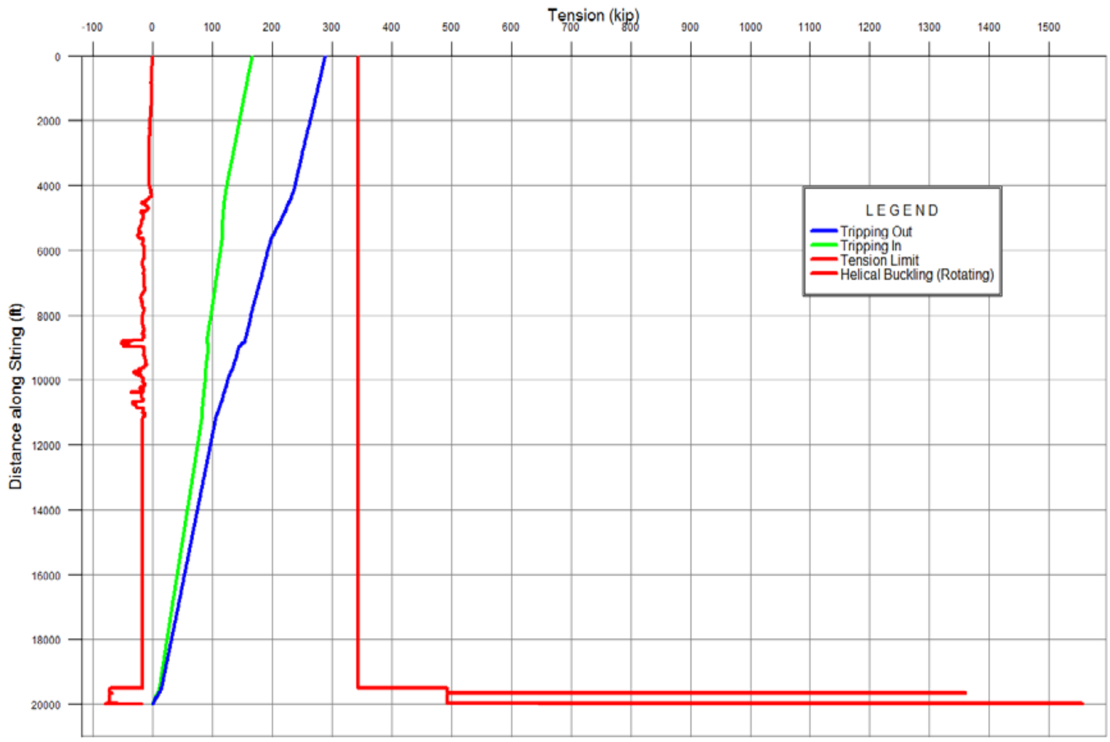
	Section Type	Measured Depth (ft)	Length (ft)	ID (in)	Drift (in)	Effective Hole Diameter (in)	Friction Factor	Linear Capacity (bbl/ft)	Item Description
1	Casing	17000,0	17000,00	9,001	8,845	6,250	0,25	0,0787	9 5/8 in, 32.3 ppf, H-40,
2	Open Hole	20000,0	3000,00	8,500		8,500	0,30	0,0702	
3									

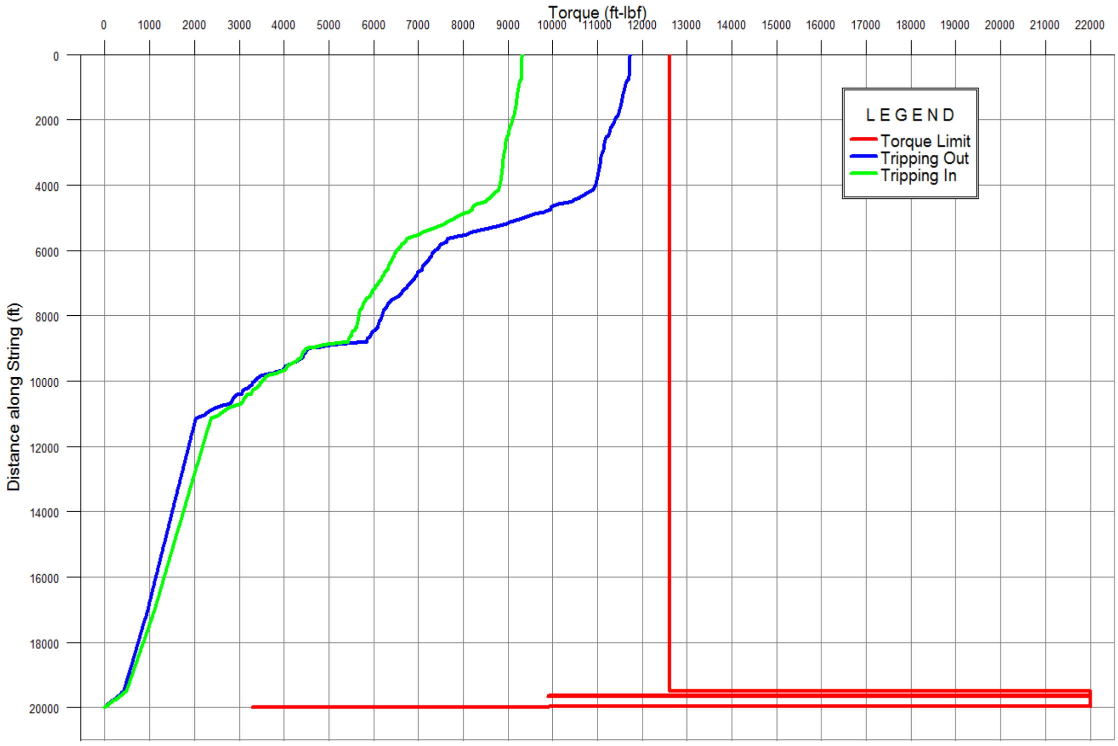
String Editor

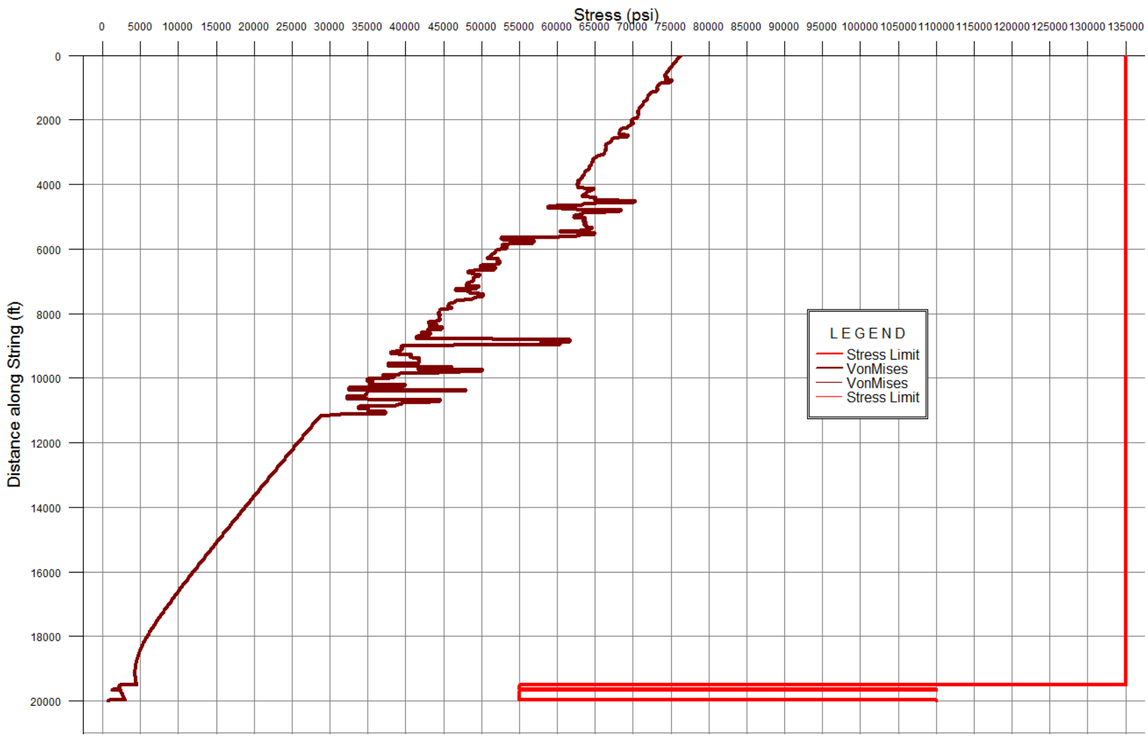
String Initialization — String Name: Assembly; String (MD): 20000,0 ft; Specify: Top to Bottom; Import String

Library — Export; Import

	Section Type	Length (ft)	Measured Depth (ft)	OD (in)	ID (in)	Weight (ppf)	Item Description
1	Drill Pipe	19508,78	19508,8	3,500	2,764	14,69	Drill Pipe 3 1/2 in, 13.30 ppf, S, NC38(IF), P
2	Heavy Weight	120,00	19628,8	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
3	Jar	32,00	19660,8	4,750	2,250	46,78	Hydraulic Jar Dailey Hyd., 4 3/4 in
4	Heavy Weight	305,00	19965,8	4,500	2,750	41,00	Heavy Weight Drill Pipe Grant Prideco, 4 1/2 in, 41.00 ppf
5	Sub	3,00	19968,8	4,440	1,440	48,11	Bit Sub 4 1/2, 4 1/2 x1 1/2 in
6	MWD	22,50	19991,3	4,750	1,600	57,70	MWD Tool 4 3/4 Sperry, 4 3/4 in
7	Stabilizer	5,00	19996,3	3,250	1,500	22,22	Integral Blade Stabilizer 4 1/8" FG, 3 1/4 x1 1/2 in
8	Sub	3,00	19999,3	3,480	1,440	26,72	Bit Sub 3 1/2, 3 1/2 x1 1/2 in
9	Bit	0,72	20000,0	8,500		85,00	Polycrystalline Diamond Bit, 0,400 in²
10							


Tension (kip)
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Distance along String (ft)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
LEGEND
Tripping Out
Tripping In
Tension Limit
Helical Buckling (Rotating)


Torque (ft-lbf)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000
Distance along String (ft)
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
LEGEND
Torque Limit
Tripping Out
Tripping In


Stress (psi)
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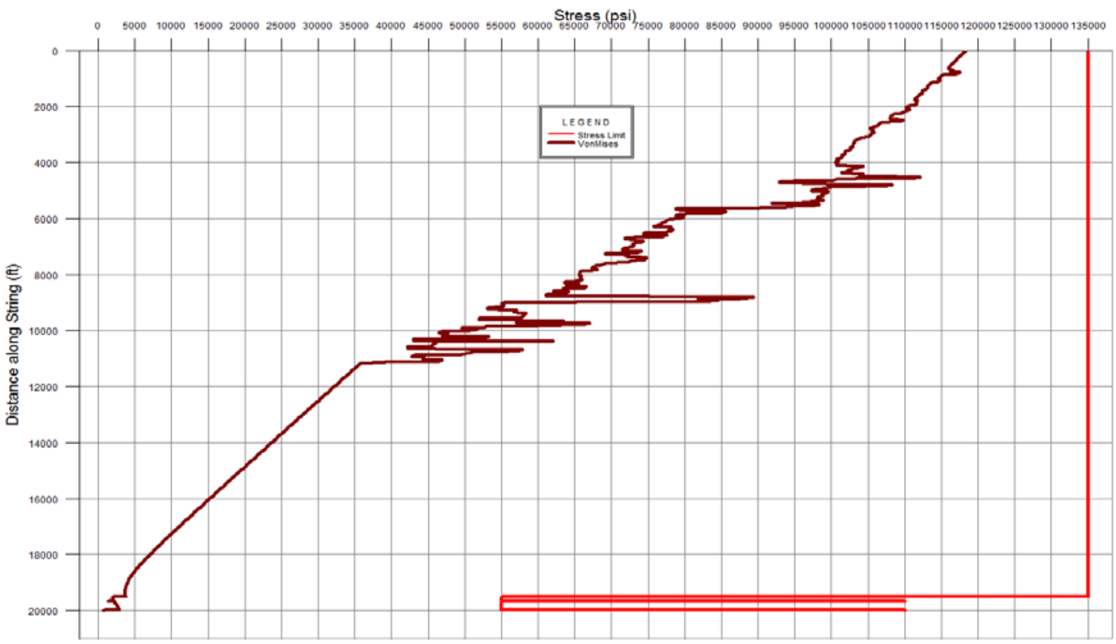
Distance along String (ft)
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000
LEGEND
Stress Limit
VonMises
VonMises
Stress Limit


Stress (psi)
0 5000 10000 15000 20000 25000 30000 35000 40000 45000 50000 55000 60000 65000 70000 75000 80000 85000 90000 95000 100000 105000 110000 115000 120000 125000 130000 135000
Distance along String (ft)
0 2000 4000 6000 8000 10000 12000 14000 16000 18000 20000
LEGEND
Stress Limit
VonMises

Appendix D: Well survey data

MD (ft)	INC (°)	AZ (°)
0	0	67,73
584,4	0,1	298
678	0,06	309,93
770,9	0,18	249,32
865,7	0,31	153,14
1045,2	0,15	117,22
1138,3	0,06	222,3
1232,9	0,13	197,58
1325,2	0,15	167,42
1398,1	0,23	185,68
1511,4	0,32	176,78
1797	0,72	186,62
1891,6	0,93	177,96
1987,3	1,22	185,23
2081,3	1,41	184,71
2175,4	1,71	188,92
2270,3	1,99	186,52
2366,7	2,11	184,49
2460,6	2,04	180,63
2555	2,56	181,46
2646,5	2,68	180,81
2732	2,8	181,89
2825,6	2,81	181,18
2918,2	2,89	178,95
3104,4	3,32	181,26
3195,7	3,26	180,69
3291	3,29	180,87
3386,9	3,24	181,77
3481,3	3,13	181,71
3575,5	3,22	179,61
3670,6	3,28	178,28
3764,1	3,42	178,59
3852,4	3,28	178,41
3947,8	3,18	179,06
4030,1	3,09	181,55
4117,1	2,9	179,33
4210,8	1,98	177,08
4395,7	0,41	144,38
4500	1,64	77,68
4585,1	4,25	68,48
4677	5,5	66,47
4774	5,47	65,41

4868,2	8,2	72,15
4957,1	9,73	68,56
5051,3	11,25	66,96
5154,8	13,44	69,7
5261,9	15,99	68,19
5341,2	17,94	66,03
5436,5	20,73	65,21
5490,5	21,77	65,44
5570,5	24,38	66,48
5648,7	26,55	66,19
5741,2	26,63	66,19
5847,2	26,74	62,77
5938,3	26,38	62,89
6026,5	25,79	63,01
6120,6	25,47	63,45
6212,6	25,15	63,59
6301	24,98	64,19
6397,1	25,72	64,27
6488,2	26,43	65,34
6582,3	26,64	65,78
6679,3	26,22	67,7
6774,2	26,23	67,67
6860,7	25,74	68
6953,4	25,33	68,18
7056,9	24,73	68,13
7150,9	24,53	68,98
7244,3	23,62	68,32
7307,6	23,69	68,09
7400,1	24,53	68,31
7490,9	25,89	67,26
7585,8	27,11	66,96
7681,8	27,72	66,36
7784,9	28,19	65,79
7866,2	27,61	66,06
7967,8	27,9	65,66
8052,2	28,21	65,41
8154,7	28,71	64,98
8248,1	29,33	64,88
8332,4	29,54	64,86
8425,5	29,43	63,48
8517,3	28,66	64,83
8610,1	29,23	64,27
8703,1	28,52	64,76
8797,4	28,81	64,82
8889,4	28,76	46,95

8985,7	28,09	64,81
9091	27,59	64,58
9170,2	27,13	64,17
9264	26,96	63,84
9365,7	25,68	63,24
9385,7	25,43	63,12
9476,6	23,77	63
9549,8	22,36	62,4
9644,5	22,33	64,24
9735,8	23,25	56,05
9832,1	25,18	67,26
9924,2	26,74	66,35
10020,9	26,39	69,8
10113,1	26,8	70,64
10202	25,97	70,79
10294,4	27,16	66,41
10391,6	27	66,47
10398,3	28,36	68,64
10577,5	29,49	64,84
10672,2	29,19	65,49
10766	33,1	69,66
10859,9	36,13	69,25
10954,1	35,22	67,54
11043,1	34,45	64,7
11140,6	31,91	62,37
11245,6	31,2	63,1

Appendix E: Well plan cutting transport models

Hole Cleaning Calculations

Calculate $n, K, \tau_y,$ and Reynold's Number

$$n = \frac{(3.32)(\log 10)(YP + 2PV)}{(YP + PV)}$$

$$K = \frac{(PV + YP)}{511}$$

$$\tau_y = (5.11K)^n$$

$$R_A = \frac{\rho V_a^{(2-n)}(D_H - D_P)^n}{(2/3)G_{fa}K}$$

Concentration Based on ROP in Flow Channel

$$C_o = \frac{\left(V_r D_B^{\,2}/1471\right)}{\left(V_r D_B^{\,2}/1471\right) + Q_m}$$

Fluid Velocity Based on Open Flow Channel

$$V_a = \frac{24.5Q_m}{D_H^{\,2} - D_P^{\,2}}$$

Coefficient of Drag around Sphere

If $R_e < 225$ then,

$$C_D = \frac{22}{\sqrt{R_a}}$$

else,

$$C_D = 1.5$$

Mud carrying capacity

$$C_M = \frac{4g\left(\frac{D_c}{12}\right)(\rho_c - \rho)}{3\rho C_D}$$

Slip Velocity

If $V_A < 53.0$, then $V_{SV} = (0.00516)V_A + 3.0006$

If $V_A \geq 53.0$, then $V_{SV} = (0.02554)(V_A - 53.0) + 3.28$

Settling Velocity in the Plug in a Mud with a Yield Stress

$$U_p = \left[\frac{4}{3}\frac{gD_c^{1+bn}(\rho_c - \rho}{aK_b\rho_c^{1-b}}\right]^{\frac{1}{2-b(2-n)}}$$

Where:

$$a = 42.9 - 23.9n$$

$$b = 1 - 0.33n$$

Angle of Inclination Correction Factor

$$C_a = (\sin(1.33\alpha))^{1.33}\left(\frac{5}{D_H}\right)^{0.66}$$

Cuttings Size Correction Factor

$$C_s = 1.286 - 1.04D_c$$

Mud Weight Correction Factor

If $(\rho < 7.7)$,then

$$C_m = 1.0$$

else

$$C_m = 1.0 - 0.0333(\rho - 7.7)$$

Critical Wall Shear Stress

$$\tau wc = [ag\sin(\alpha)(\rho_c - \rho)D_c^{1+b}\rho^{b/2}]\frac{2n}{2n - 2b + bn}$$

Where:

a = 1.732

b = -0.744

Critical Pressure Gradient

$$Pgc = \frac{2\tau wc}{r_h[1-(\frac{r_p}{r_h})^2]}$$

Total Cross Sectional Area of the Annulus without Cuttings Bed

$$A_A = \frac{\pi}{4}\frac{(D_H^2 - D_P^2)}{144}$$

Dimensionless Flow Rate

$$\prod g_b = \prod[8\times\frac{\frac{n}{2(1+2n)}}{(a)\frac{1}{b}}]^{\frac{1}{2-(2-n)b}}\times(1-(\frac{r_p}{r_h})^2)(1-(\frac{r_p}{r_h})^{\frac{b}{2-(2-n)b}}]$$

Where:

a = 16

b = 1

Critical Flow Rate (CFR)

$$Q_{crit} = rh^2\left[\frac{\rho g b^{\frac{1}{b}} r_h^{\left(\frac{1}{b+n}\right)}}{K\rho^{\left(\frac{1}{b-1}\right)}}\right]^{\frac{b}{2-b(2-n)}} \prod_{gb}$$

Correction Factor for Cuttings Concentration

$$C_{BED} = 0.97-(0.00231\ \mu_a)$$

Cuttings Concentration for a Stationary Bed by Volume

$$C_{bovc} = C_{BED}\left(1.0-\frac{Q_m}{Q_{crit}}\right)(1.0-\phi_B)(100)$$

Where:

D_B = Bit diameter

D_H = Annulus diameter

D_P = Pipe diameter

D_{TJ} = Tool joint diameter

D_C = Cuttings diameter

τ_y = Mud yield stress

G_{fa} = Power law geometry factor

R_A = Reynolds number

R_e = Particle Reynolds number

ρ = Fluid density

ρ_c = Cuttings density

V_a = Average fluid velocity for annulus

V_R = Rate of penetration, ROP

V_{CTV} = Cuttings travel velocity

V_{so} = Original slip velocity

V_{SV} = Slip velocity

V_{CTFV} = Critical transport fluid velocity

V_{TC} = Total cuttings velocity

K = Consistency factor

n = Flow behavior index

a, b, c = Coefficients

YP = Yield point

PV = Plastic viscosity

Q_C = Volumetric cuttings flow rate

Q_m = Volumetric mud flow rate

Q_{crit} = Critical flow rate for bed to develop

C_o = Cuttings feed concentration

C_D = Drag coefficient

C_m = Mud carrying capacity

C_A = Angle of inclination correction factor

C_S = Cuttings size correction factor

C_{mud} = Mud weight correction factor

C_{BED} = Correction factor for cuttings concentration

C_{bmc} = Cuttings concentration for a stationary bed by volume

U_{sr} = Settling velocity

U_s = Average settling velocity in axial direction

U_{mix} = Average mixture velocity in the area open to flow

α = Wellbore angle

ϕ_B = Bed porosity

μ_a = Apparent viscosity

λ_p = Plug diameter ratio

g = Gravitational coefficient

r_0 = Radius of which shear stress is zero

r_p = Radius of drill pipe

r_h = Radius of wellbore or casing

P_{gr} = Critical frictional pressure gradient

τ_{w} = Critical wall shear stress