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MASTER THESIS

Title: Analysis of Equivalent Circulation Density Management in Drilling Operations

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Abstract

Drilling fluid is an integral part of the drilling and completion processes of the well, so the successful delivery of the well depends strongly on this key component. Without using drilling fluid none of the well operations can be carried out, so mud is used in every single step of the operations. That is the reason why properties of drilling mud are controlled and modified for the particular activity in the well. Drilling fluids play an important role in providing well control and stability during drilling operations. During drilling operations because of movement of the drilling pipe and casing in the wellbore, high pressures created in the wellbore and this is presented in terms of the equivalent circulating density (ECD).

This thesis contains drilling fluid management in different well and wellbore conditions on the casing operations. The focus of the study is on the ECD optimization during running casing into the wellbore, mud conditioning and cementing of the casing in place. Initially, an extensive literature review is carried out on the discipline and then by using software approach, on the Drillbench Software well models are created. Hence, as a resource of research in the North Sea Gullfaks field, 2 wells are chosen and their data is used for the simulation purposes. By changing wellbore structure, new well designs are proposed for both of the wells. After designing new casing structures, the feasibility of changing this design is analysed and for this purposes, mud program, cementing program are established for simulation.

During the simulation, by optimizing running speed, surge analysis is carried out, where higher ECD causing fracturing wellbore is prevented and also limits of the operations in each well are examined. Then, mud conditioning is carried out in both of the wells and in this case again ECD causing hole problems are forecasted so theoretically became preventable. Finally, a number of cement program are developed for the casing cementing and according to the obtained ECD in the wellbore, the best option is chosen for each wellbore conditions. Moreover, gel model and mud rheology are also investigated and their effect on the operations mentioned above presented. Also, equivalent viscosity changing during the cementing is examined. After results obtained from the simulations feasibility of changing wellbore structure is studied.

Nowadays, it is undeniable that in order to have a successfully drilled wells the engineers have to gain a full control of the wellbore hydraulics at the all sections until the target point. Dynamic Drilling Simulation Software such as Drillbench is established to help us on these issues during drilling the wells.

Analysis on the Drillbench software and technical literature as well as papers review demonstrate that optimization wellbore pressures caused by pipe movement and drilling fluid flow

are possible whereby doing so wellbore stability is under control. Also by choosing the best rheology for the fluids, ECD in the annulus is minimized.

Xülasə

Qazıma məhlulu quyunun qazılma və tamamlanma prosesinin daxili bir hissəsidir, bu minvallada quyunun uğurlu təhvil verilməsi bilavasitə bu həlledici komponentdən asılıdır. Qazıma məhlulu istifadə edilmədən heç bir quyu əməlliyyatı icra oluna bilməz, beləliklə qazma məhlulu əmaliyyatların hər bir mərhələsində istifadə edilir. Buna səbəb olaraq qazıma məhlulunun xassələri nəzarət altında saxlanılır və quyudakı müvafiq tapşırıqlara uyğun dəyişdirilir. Qazıma məhlulları quyuya nəzarət və sabitliyin qazma vaxtı saxlanılmasında əhəmiyyətli rol oynayır. Qazıma əməlliyyatları zamanı qazıma borusunun və qoruyucu borunun quyuda hərəkətinə görə quyuda yüksək təzyiq əmələ gəlir və bu da ekvivalent dövrüyyə sıxlığı (EDS) kimi təqdim olunur.

Bu tezis qazıma məhlulunun müxtəlif quyu şəraitlərində qoruyucu kəmərin oturtulması zamanı idarə olunmasından bəhs edir. Təhdid olunan əsas məsələ qoruyucu kəmərlərin quyuda quraşdırılması, qoruyucu kəmər buraxıldıqdan sonra qazıma məhlulunun dövriyyəsi və sementləmə zamanı EDS-nin optimizasıyasıdır. İlkin olaraq, bu sahədə geniş ədabiyyat icmalı baxışdan keçirildi və sonra proqram təminatı yanaşması ilə “Drillbench” proqramının köməyi ilə quyu modelləri hazırlandı. Aparılan tədqiqatda mənbə olaraq Şimal Dənizindəki Gullfaks yatağında qazılan iki ədəd quyunun məlumatları simulasiyanın qurulmasında istifadə olunub. Quyuların quruluşlarını dəyişməklə hər iki quyuya tamamən yeni qoruyucu boru dezaynları təklif olunur. Yeni təklif olunan dezaynların mümkünlüyü yoxlanılır və buna yeni qazma və sement məhlulu proqramları hazırlanıb simulasiya edilir.

Simulyasiya zamanı, quraşdırılma sürətini optimizasiya etməklə dalğa analizi aparılıb, beləki bu zaman yüksək EDS-nin nəticəsində quyunun yarılması təziyiqi bilnib və qarşısı alınacaq limitlər hər bir quyu üçün ayrılıqda müəyyənləşdilib. Son olaraq, sement proqramı quyudan əldə olunan EDS-ə əsasən yaradılıb və hər bir quyu şəraiti üçün ən yaxşı variant seçilib. Bundan əlavə olaraq, simulyasiyadan nəticələr əldə edildikdən sonra quyu quruluşunun strukturunun dəyişdirilməsinin mümkünlüyü öyrənilib.

Günümüzdə, müvəffəqiyyətlə qazılmış quyu əldə etmək üçün mühəndislər quyunun hidravlikasına hədəf nüqtəsinə qədər hər bir sessiyada tam nəzarət edə bilməlidirlər. Dinamik Qazıma Simulyasiyası Proqramı olan “Drillbench” quyuların qazılması zamanı bunları etməyimizə imkan vermək üçün yaradılıb.

“Drillbench” proqramında aparılan analizlər və texniki ədabiyyatın icmalı onu göstərirki, boru hərəkəti nəticəsində və qazıma məhlulu axınına görə yaranan təzyiqləri optimizasiya etmək

mümkündür. Beləki, bunu etməklə quyunun stabilliyi nəzarət altına alınır. Həmçinin, qazıma məhluları üçün ən yaxşı xüsusiyyətlərin seçilməsi də EDS-i həlqəvi fəzada minimuma endirir.

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Nomenclature

List of Acronyms

ECD	Equivalent Circulating Density
ERD	Extended Reach Drilling
MWD	Measurement While Drilling
LWD	Logging While Drilling
ROP	Rate of Penetration
WBM	Water Based Mud
OBM	Oil Based Mud
NAF	Non-Aqueous Fluid
OWR	Oil Water Ratio
RPM	Revolutions per Minute
LCM	Lost Circulation Material
TD	True Depth
OD	Outer Diameter
ID	Inner Diameter
PPFG	Pore Pressure Fracture Gradient
SPP	Slow Pump Pressure

List of Symbols

Symbol	Definition	Unit
PV	Plastic Viscosity	Pa·s
YP	Yield Point	Pa
P_{total}	Pump Pressure	MPa
P_{hyd}	Hydrostatic Pressure	MPa
$P_{frictional}$	Frictional Pressure Drop	MPa
ρ	Density	sg
T	Temperature	^{0}C
h	Depth	m
g	Acceleration due to gravity	m/s^2

INTRODUCTION

Research Background

Drilling fluid or sometimes referred as a drilling mud or simply mud is crucial integral part of the modern rotary drilling system. Generally, it can be a liquid, gas or gasified liquid circulating fluid used in drilling process in order to perform a number of different functions required for successfully drilling a usable wellbore at the lowest overall well cost. Although cost of mud is comparatively lower than rig or other components of the drilling facility, selection of proper mud and maintaining it in desired state, has a significant effect on the drilling operation. Drilling fluid properties affects every single operation in the well, so maintaining mud in good condition is key in terms of both wellbore stability and cost efficiency of the well. So, the success of the rotary drilling process significantly depends on drilling fluids.

Although, water was used in China as a softening agent in drilling several hundred meters in a depth as early as 600 BCE, the first practice of circulating fluid while drilling is introduced in England in 1845. For long period of time generally water based drilling fluids are used for drilling operation and in order to control and make changes in the properties of muds, different additives are used. In 1960, with introduction of the oil-based mud, there was a significant improvement in drilling performance. However, because of the environmental issues, some regulations are applied to use of it. In the 1990s, synthetic-based fluids were developed, which had good drilling performance and it complied with strict regulations governing offshore fluid and cutting disposal. Drilling fluids properties are modified according to the particular activity that is carried out in the borehole. It is very important to maintain all the properties the same in phase of the activity, so any change is an indicator of the abnormalities in the borehole. [1]

In this thesis, drilling fluid behaviour, its rheology effect on the wellbore pressures are investigated. Hence, by using casing operations in the wellbore, ECD optimization is carried out. The importance of this analysis is to have safe operations in the wellbore and define operational limits during the carrying out these. Hence, problems in the wellbore are closely related to the cost of the well and also safety of the rig, rig personnel.

Statement of Problem

The key area of the research is divided into several sections, where firstly extensive literature review is carried out on the ECD optimization in different wellbore conditions. Also during literature review, equivalent viscosity is examined and its change depending on the well parameters are investigated. In the second section, by using software approach to the problem, ECD optimization was carried out while casing operations. Hence, in order to understand mechanics of the ECD change in the wellbore based on the literature review, wells are chosen in the North Sea and by using details of these wells mud program, cementing programs are established for different sections of the casings. Also, equivalent viscosity change while casing cementing is evaluated by using software approach.

Objectives of Problem

The aim of this project is to study drilling fluid circulation system by using several well models. The main objectives of this project are:

- Analysis of drilling fluid properties and rheology in different well conditions and assessment of mud properties at different well cases

- ECD management in circulation during different phases of drilling operations by using software approach

- Design drilling fluid for different wells and wellbore cases in field

Scope of the Work

The research concentrates drilling fluid behaviour in different phases of the drilling operations, where the thesis is divided into two sections, where firstly equivalent circulating density while drilling and cementing operations has been discussed. In the section, factors affecting to ECD during drilling is analysed and it is followed by circulation properties in extended reach drilling operation hole cleaning is discussed very deeply. Moreover, recent laboratory work has been analysed. Also, importance of the ECD management prior to and during cementing of the casing strings is discussed and example of the work that has been done is analysed.

Secondly, obtained literature review data is used to build 2 well models in the Drillbench software and according to the scope of the work, the casing designs including casing sizes and their setting depth are changed. Then by using software analysis, then whether this change is hydraulically is feasible or not is studied.

The research study will take different wellbore sections and conditions into account where safe drilling operations by drilling fluid and ECD standpoint are discussed. Moreover, change in rheology of mud and its effect on the pressure created in the wellbore, at the same time gel model are studied in the thesis.

CHAPTER 1. LITERATURE REVIEW

This chapter provides information about extensive literature review that was carried out drilling fluid, ECD managements and rheological properties of the mud. The first part of the literature review mainly concentrates on the theoretical background of drilling fluids, on the other hand, the second part of it concentrates on the management of problems that is generated during circulation process, and their relation to further work that is going to be done is presented.

1.1 Theoretical Background of Drilling Fluids

During typical drilling operation in circulation system, drilling fluid is firstly mixed in large tanks and then it is pumped to the well by using large mud pumps and surface equipment. At the bottomhole it comes out through the bit and enters to the annulus where it carries cuttings to surface that are generated by the bit to the surface. At the surface mud cuttings are removed by using solid removal equipment. After ensuring that mud is cleaned from cuttings and maintains its original properties, it is recirculated. If it has lost its original shape, mud is not able to carry out its functions, then particular chemicals are added into the drilling fluids in order to re-establish its original properties. In the Figure 1.1, main components of the drilling mud are presented [2].

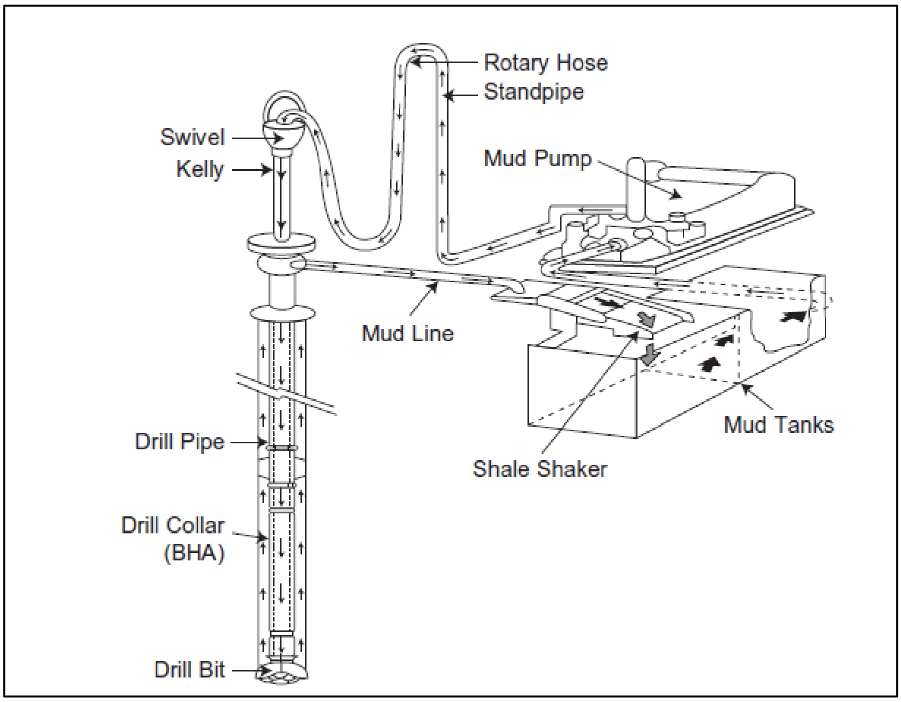


Figure 1.1. Drilling fluid circulation system [2]

During drilling operation change in drilling fluid properties is inevitable, in the openhole cuttings, influx from formation, unstable formations and especially different temperature and pressure zones cause changes in properties of the drilling fluid. Mud density, viscosity, gel strength, filtration rate and other properties are affected by the temperature of formations. So, it important to take thermal properties into account, where their relationship with other drilling fluid properties plays a significant role while establishing whole circulation system for a particular phase of the operation in the well.

Initially, when drilling fluid has entered into the drilling operations, it was regarded as a drilling tool which carried cuttings to the surface. However, now it is one of the most important factors that success or failure of the hole depends primarily on it. For these reasons, composition and properties of drilling fluid are key factors when establishing new drilling fluid system for the particular phase of the drilling operations. Depending on properties of mud, the functions vary, however these are key functions of drilling fluids [3]:

- Clean hole from cuttings
- Maintain enough hydrostatic pressure to prevent flow of formation fluids to wellbore
- Maintain wellbore stability
- Cool and lubricate drillbit and drillstring
- Transport hydraulic horsepower to mud motor and drill string components
- Transmitted data to surface in terms of pressure pulses
- From a filter cake in the permeable walls

Drilling mud has also a number of benefits to the drilling procedure and they can be considered as a secondary or minor functions of the drilling mud. Generally drilling fluids are divided into 3 categories according to the continuous phase and they are a) pneumatic or gas drilling fluids b) water based drilling fluids c) oil based drilling fluids [1].

In water based mud, continuous phase is water and it is considered as a least expensive drilling fluid and it is most commonly used. Its major disadvantage is they cause wellbore instability with shale. However, with inhibitive water based muds, this problem is solved.

In oil based muds, the continuous phase is oil and their major advantages are they provide good wellbore stability, good lubrication between wellbore and drillstring, temperature stability and low formation damage. Their major disadvantage is that they are expensive and they require good handling in terms of pollution control. However, they cause less wellbore stability problems than the WBM [3].

In order to establish drilling fluid system different kinds of additives are added to the drilling mud. Additives can be active where they can react with continuous phase and chemicals inside of it and they also can be passive where they do not react. These additives generally are viscosifiers, viscosity reducers, weighting materials, fluid-loss reducers, lost circulation materials and special additives. Lost circulation materials are used in order to prevent loss of drilling fluid into the permeable formations and in the case of lost circulation. Lost circulation occurs when the hydrostatic head of drilling fluid or ECD in the wellbore is higher than formation fracture gradient and fracture of formation occurs. Drilling fluid viscosity and its yield point are measured by using multi-rate Fann viscometer. Another property of the drilling mud is filtration, which is used to estimate the rate at which fluid from mud is forced to through a filter under specified temperature and pressure. It is also important to state that although SI unit for the density is kg/m3 and for the pressure gradient it is Pa/m, in the petroleum industry generally same units are used for them. That’s why pressure gradient is presented in density units, where it is estimated with $\rho=\frac{P/h}{g}$ [3].

1.2 ECD Management

ECD management is very crucial part of the drilling operations, where it can lead to a number of issues in the well.

1.2.1 ECD Management during Drilling Process

Prior to drilling operations drilling program is prepared according to the given formations and wellpath that are going to be penetrated. As part of the drilling program, mud weight should be between formation pore pressure and formation fracture gradient, where if it falls below pore pressure then possible formation fluids influx can occur to the wellbore and as result severe well integrity problem can occur. On the other hand, if it is higher than formation fracture gradient then breaking down of the formation and possible loss of circulation may occur. On the hand, generally in extended reach drilling (ERD) wells mud window is determined by hole collapse gradient and formation fracture gradient. The value of hole collapse gradient is higher than pore pressure, where borehole collapse occurs when the drilling fluid pressure is too low to maintain the structural integrity of the drilled hole [4]. The associated problems are pipe sticking and possible loss of well. So, it is important to control downhole pressures and in this case mud properties such as density, viscosity and fluid loss are key for controlling. Density affects hydrostatic pressure in this wellbore, while viscosity and fluid loss influence the fluid friction. When drilling fluid is circulating through the drillstring, pressure at the bottomhole will be greater than hydrostatic head of the fluid column and this is due to extra pressure is applied to the surface because of the frictional pressure losses in the annulus while fluid flows from the bottomhole to the surface [2]. The equivalent circulation density is the measure of the combined effect of the hydrostatic pressure of the fluid and created frictional pressure drop in the annulus [4]:

$$ECD=\frac{P_{total}/TVD}{g} \tag{2.1}$$

Where $$P_{total}=P_{hydrostatic}+P_{friction} \tag{2.2}$$

Smaller annular clearance will decrease flow area, which in turn will increase ECD and if ECD exceeds formation fracture gradient then fracture of formation occurs. Below, in Figure 1.2 the 2 wellbores are illustrated, with bigger and smaller annular clearances.

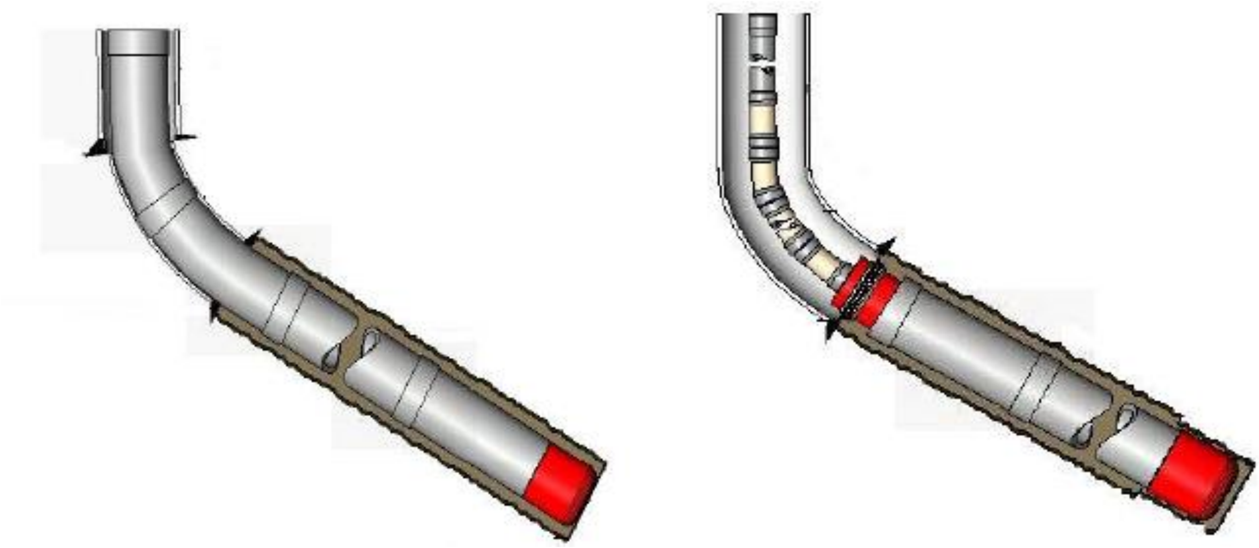


Figure 1.2. On the left bigger borehole with annular clearance and on the right smaller annular clearance [5].

During drilling operations to control reduced ECD is very crucial. Reduction in ECD's can be caused by reducing pump rate, lowered mud density or different mud properties. The main factors that affect ECD Management during the operations are [6]:

- Cutting loading in wellbore
- Transient Thermal effects (axial conduction and radial convection)
- Thermal and pressure effects on the rheology and density
- Dynamic Surge and swab effects
- Thermal and pressure effects on the wellbore stability

The case study has been carried out on the B5 well in Pierce field in the North Sea, where because of the weak formation loss has been occurred during the drilling of the reservoir section. The reservoir was depletion drive reservoir although water injection into reservoir has been carried out, because of the uncertainty in the connection between injector and producers it was difficult to estimate accurate reservoir pressure [7]. As a result of the depletion minimum horizontal stress reduced. The formation was weak and any time losses could occur during the drilling operation, where weight was required to be reduced, however in this case mud weight is determined by shale collapse gradient and decreasing it was not possible due of the small mud window. As a result in order to strengthen the formation special wellbore strengthening materials were added to the drilling mud. However, despite the remedial techniques losses occurred due to high ECD occurred during drilling [7].

In order to prevent such loss in the planned A11 well which was located in the field as well B5 during drilling key was ECD management. Drilling fluid properties are closely monitored to ensure the ECD was kept as low as possible since it would likely to exceed minimum horizontal stress based on possible real low pressure.

The problem with setting a maximum ECD limit on a well with tight drilling program and a "Standard non-aqueous fluid (NAF) system" is that it can be only achieved by decreasing rate of penetration (ROP) and flow rate. However, decreasing ECD in deviated wells can lead poor hole cleaning, where cuttings can form beds in the open hole and as a result, it will cause an increase in the ECD by reducing flow area. This creates very big wellbore stability problem, where loss of the hole section can occur. The wells in the field are horizontal wells without using a low-ECD drilling fluid system, it is difficult to balance clean hole from cuttings and cutting generation. In a successful system, by using low viscosity drilling fluids ECD is reduced and at the same time drilling fluids carrying capacity is not affected. This can occur in the following conditions:

- Dynamically; occurs under conditions of low shear in the annulus and it is related to the mud weight and hole angle
- Where the drilling fluid is stationary for long period of time (static sag)
- During logging of periods of low circulation where gels are continuously broken.

In order to achieve a low ECD drilling fluid system by considering its resistance to barite sagging is in the oil water ratio (OWR) coupled with optimum organophilic clay content. The study shows that for a low ECD fluid, high OWR NAF is more resistant to the barite sagging than low OWR NAF, due to a higher concentration of the organophilic clay in the NAF system. As a result of successful execution of the drilling operation and by using these low ECD drilling fluid strategy, no losses occurred [6].

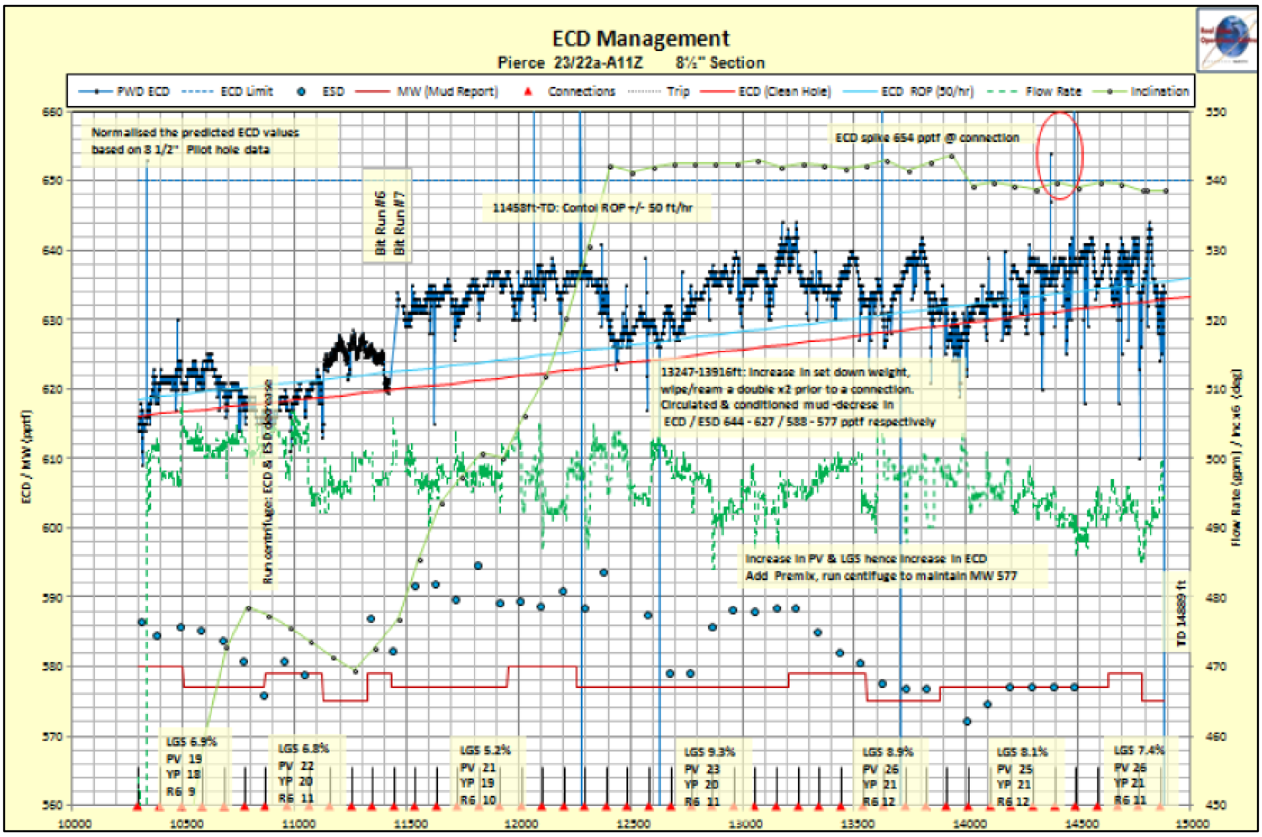


Figure 1.3. Drilling Parameters Pierce A11 main bore. [7]

Analysis of Figure 1.3 reveals several key points related to the ECD trend. ECD has increased 1)due to the poor hole cleaning in the horizontal hole section 2)because of the viscosity rise through the addition of the marble. ECD has decreased due to

- Use of centrifuges and dilution with premix to a higher OWR
- Drop in the rate of penetration (ROP) while drilling limestone rocks
- Additional circulation of the hole for better cutting removal while connections are made
- Increased rotary RPM (revolutions per minute) from 150 rpm to 180 rpm at TD for better hole cleaning.

In depleted reservoirs where drilling windows are very narrow, then a low ECD drilling fluid and ECD management strategy is a potential alternative to wellbore strengthening, however application of the LCM is also required.

In the case study where BP carried out operations in Amberjack field, there were problems and the solution for these problems was discussed. The field had been being developed since 1983 and trouble happened in A16 ST1, where after 244 mm casing, next section drilling operations were started [8]. Hence, due to small mud window for the next section, annular pack-off, stuck pipe and lost circulation occurred. It caused some difficulties in each sidetrack wells and as a result of it, a lot of time and cost from the operations had been lost. After 2 days spent to maintain wellbore integrity, sidetrack operation was initiated and 0.025 - 0.028 m^3/s mud with 1.74 sg density was circulated and 12.242 m^3 of mud were lost while circulating newly drilled section. Then after mud window is tested to 1.82 sg, mud weight has been decreased to 1.64 sg from 1.71 sg. With this mud weight well section drilled and before reaching TD stuck pipe occurred 2 times where once 5300 units of swab gas entered to the annulus. However, during continuing operations, trip gas was around 2000 units and 31.797 m^3 further mud were lost, which eventually required to increase mud weight 1.73 sg. Despite having, such severe wellbore stability problems, finally TD was reached. This heavy drilling operational problems were repeated in well A25 and several other wells, so in order to maintain borehole stability, reduce the ECD, avoid mud losses and minimize NPT in this field and others similar fields, Managed Pressure Drilling (MPD) technique used [8].

The purpose of the MPD is to reach TD at planned time by avoiding unplanned sidetracks, losses and the other non-productive events that occurred in drilling of previous wells. MPD is designed for particular wells, where it keeps BHP in the wellbore between maximum pore pressure and minimum fracture gradient. Hence, in the particularly A16 ST1 well, the systems a dynamic annular pressure control (DAPC) system which has automated, programmable control system integrated with real-time hydraulics simulator, automated choke manifold and backpressure pump, a pressure relief choke, a Coriolis meter for kick detection, and high pressure rotating control device (RCD).

When the system detects kick in the well, then RCD closes BOP and according to the software calculation, DAPC applies backpressure. When DAPC detects a change in the ECD it adjusts choke so that measured backpressure reaches to the calculated point. Also in order to compensate ECD change in the trips, pressure input is entered into the system, where the system itself adjusts choke. The system has been tested on the A12 ST1 well, where for BHP input minimum fracture gradient of 1.83 sg and maximum pore pressure of 1.76 sg were entered to MPD system. In Figure 1.4 planned hydraulic model for the A12 ST1 well is presented.

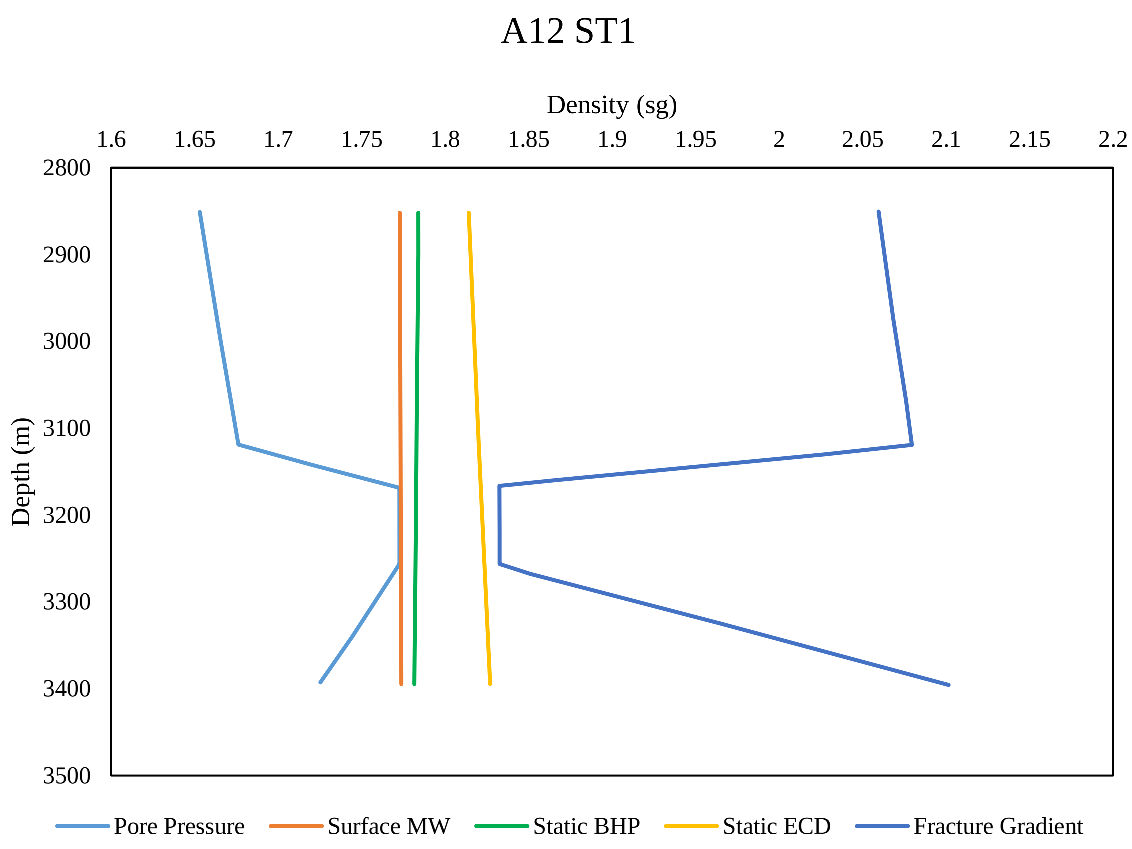


Figure 1.4. Planned hydraulic model for A12 ST1 well [8].

Circulation rate was also limited because ECD and slow pump pressure (SPP) and in the particular case 0.038 m^3/s was the maximum margin. During drilling operations, to help hole cleaning and cutting removal, high viscosity sweeps were circulated in regular intervals. According to the simulation, BHP had to be kept at 1.78 sg ECD value, due to safety margins in the well. The main fluctuation in the well happens because of the connections, where because of the change in pump pressure, ECD changes extremely and as a result, ECD cannot be properly controlled and it leads to kick and loss circulation. However, connections are the events that are planned and they are manageable, while there can be events that can happen very fast and it is extremely difficult to manage such changes. In the case of unannounced, stimulated fire drill, driller uses hard stop the rig pumps which stops pumps in just 30 seconds. System responds to change in 20 seconds, BHP changes around 0.018 sg. When pumps start, 45 seconds is required to stabilize BHP [8].

1.2.2 ECD Management in ERD Well Hole Cleaning

ECD management becomes more critical in ERD wells and the case study has been carried out in Japan when in order to initiate geothermal development drilling of new wells were required. However, because of the majority of the geothermal resources were located in the natural parks and as a result ERD wells were an only eco-friendly option. In ERD wells key issue is hydraulics and because of the possible lost circulation zones, it was only possible to use low density and low viscosity drilling fluids. However, this kind of drilling fluids cutting carrying capacity is low, so balancing low ECD and high carrying capacity is very difficult is such wells. In this study, a number of cutting transport experiments were carried out, using a large-scale flow-loop apparatus and field measurements of annular pressure while drilling method in a recently drilled geothermal directional well in Japan [9].

In order to model drilling fluid for the drilling operations, transient cuttings transport simulator has been used. This simulator predicts the transient behaviour of the annular pressure, cutting bed height, suspended cutting concentration, and phase velocities along the entire trajectory of the well. During the experiment firstly, all the data has been obtained from existing exploration wells and from results of the simulation, it was clear that cutting deposit bed formed along the tangential section. Then frictional factors were modified by match measured and simulated ECDs.

In order to simulate the obtained results on the extended reach geothermal wells, firstly model has been established with 3000 m total depth and 2500 m horizontal departure and the maximum hole inclination angle of 70^0 [9].

Simulation is carried out on the 311 mm section of the well with both water and mud 2 (bentonite mud). It has been assumed that ROP was $2.5 \cdot 10^{-3}$ m/s and 1 hour circulation has been done after 1 stand of drilling. Results of simulation are presented in Figure 1.5.

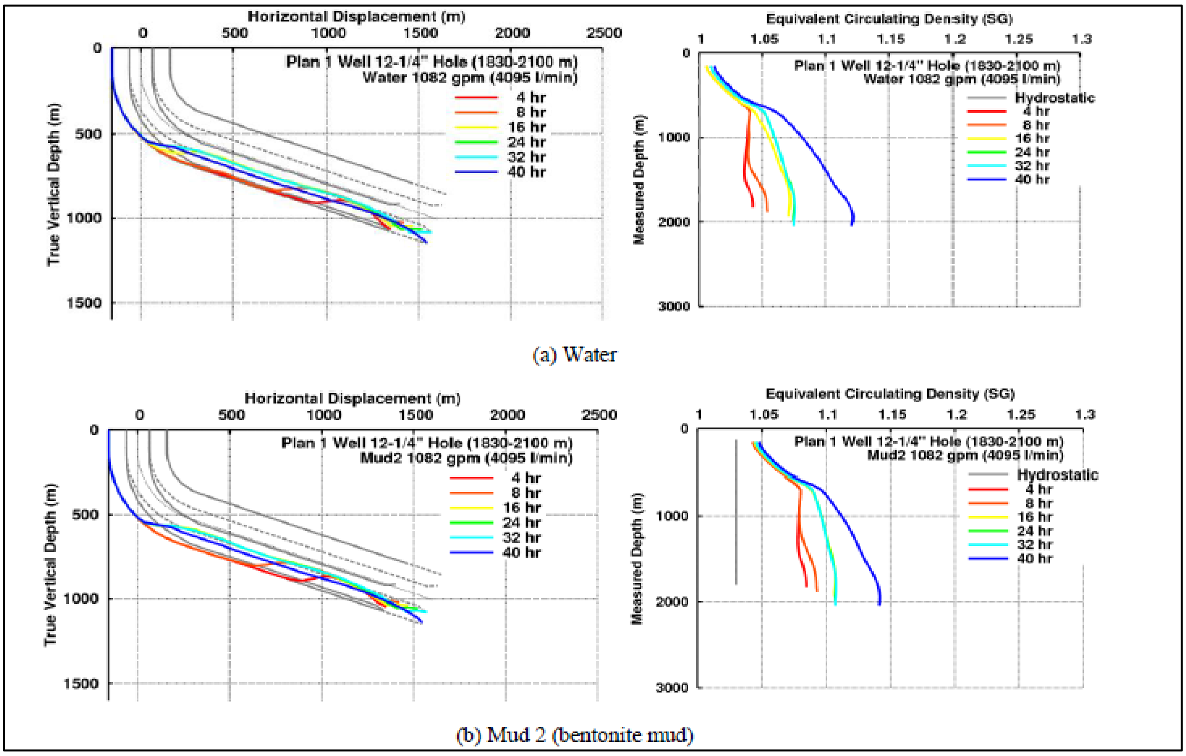


Figure 1.5.Simulation result for Plan 1 model well 318 17.5mm hole section. [9]

In this case, circulation rate was 0.068 m^3/s and corresponding annular velocity was 1.08 m/s. This value is slightly smaller than desired value which is 1.4 m/s, so maximum circulation rate of 0.068 m^3/s is insufficient for completely avoiding formation of the cutting bed. However, in this value of circulation rate relatively good hole cleaning is achieved and ECD is kept low, although not all of the cuttings were cleaned from hole [9].

1.2.3 ECD Management in Cementing Narrow Pressure Window

When the casing is in the bottom of the hole because of smaller annulus, during cementing problems can be caused by high ECD in the annulus. As a result, zonal isolation in narrow pressure windows has always been challenging and during cement job slurry losses are encountered, so for the better wellbore stability and avoiding potential losses are achieved by accurate pressure data. The introduction of the extended reach drilling (ERD) wells has brought additional challenges not only to the drilling of the sections but also running casing, cementation as well. The objectives are cementing are sealing around the shoe weaker formations and provide zonal isolation to the potential flow zones. In addition to the challenging ECD management in the smaller clearances, it is also very difficult to achieve uniform cement job around the casing. Smaller clearances increase the frictional pressure drops and in the case of small pressure windows, the probability of the occurrence of the losses also increases. However, controlling ECD is possible by using lightweight mud or spacer ahead of the cementing [5].

While designing cement the 2 things generally are taken into account: slurry property and displacement mechanism. Displacement mechanics involves complete displacement of the drilling mud from annulus by the cement, which is considered primary cement job and it significantly depends on annular clearances, standoff ratios, density and rheological hierarchies between displaced and displacing fluids, pipe movement, and pressure/velocity gradients. Generally, it is industry-accepted practices considers that there should be 10% hierarchies in densities and rheology of displaced and displacing fluids [5]. Casing rotation and reciprocating and also high circulation rate will assist better cleaning of the cuttings, removing filter cake on the walls and degrade gelled mud in the annulus. It is also, commonly accepted practice to pump low-density Newtonian fluids ahead of weighted spaces to achieve reduction in the ECD, and thereby enabling slurries to be displaced at a more optimized displacement rates required for effective mud removal. However, in terms of displacement efficiency smaller holes are better, but again it is important taking displacement rate, the rheology, and the overall geometry of the hole into account. In ERD wells, the hole size significantly depends on the ECD and ability to run casing to the planned depth. That's why open hole is under-reamed for increasing annular clearance, where velocity of the fluid decreases and removal of the gelled mud becomes more difficult.

Drilling fluids properties are not suitable for cementing hence, mud has to be conditioned prior to cementing [3]. During mud conditioning, its density is decreased without compromising well control, where ECD at the bottom of the well is not changed. Decreasing muds gel strength, yield stress, yield point and plastic viscosity is beneficial. Doing so reduces the driving forces required to displace the mud and increases mud mobility. Drilling mud is also circulated when casing is on the bottom of the hole. In that particular case, flow rate stages up with 0.00265 m^3/s increments to maximum planned displacement rate. It also changes the wettability of the wellbore and casing, where they become water wet and as a result bonding of the cement and casing and open hole becomes much better. Moreover, during mud circulation, it is possible to detect fluid influx or losses into the well prior to cementing. Circulation also erodes the gelled or dehydrated mud that is trapped in washouts, on the narrow side of an eccentric annulus and on the walls of the permeable formations.

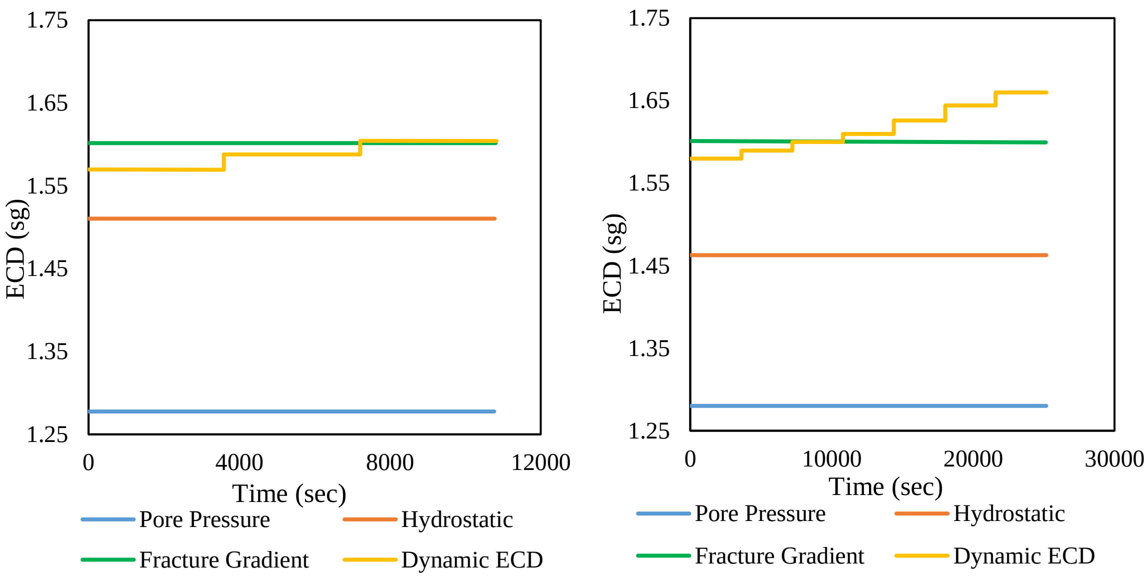


Figure 1.6. ECD at casing shoe while casing on the bottom, with original mud weight 1.51 sg mud (left) and with conditioned mud weight 1.46 sg mud (right). [5]

As can be seen from Table 1.1 and Figure 1.6 with 1.51 sg mud weight it is possible to circulate at 0.0053 m^3/s without exceeding formation fracture gradient and after conditioning mud, with 1.46 sg mud weight it is possible to circulate at 0.0159 m^3/s without fracturing the formation.

Table 1.1. Circulation rate with 1.46 sg mud weight (left) and with 1.51 sg mud weight (right). [5]

Rate m^3/s	Duration sec	Volume m^3
0.0132	360	47.69
0.0159	360	57.23
0.0185	360	66.77

Rate m^3/s	Duration sec	Volume m^3
0.0026	360	9.53
0.0053	360	19.07
0.0079	360	28.61

1.2.4 Drilling Fluid Rheological Properties at Different Pressures and Temperatures

In order to understand the rheological behavior of the drilling mud in the wellbore conditions, another test has been carried out on drilling fluid by using modified Fann consistometer. During the test behavior of change of viscosity of the drilling fluid in different pressures and temperatures are investigated and it is compared with other drilling fluids with different mud weights [10].

During the test, first, the equipment is calibrated by using tap water and silicone oil with known viscosities and then by using Fluid A, which is an invert emulsion mud with 1.01 sg mud weight is tested at different pressures. As can be seen from Figure 1.7, the rate of increase in the equivalent viscosity decreases with increase in temperature at a constant pressure, where it is clear that this increase is sharp with increasing pressures. On the other hand in sample B, which has 1.25 sg density, at 65.56 ^{0}C equivalent viscosity increases 5 times at 137.89 MPa compared to 6.89 MPa. While there is a continuous decrease in the value of equivalent viscosity as temperature increases [10].

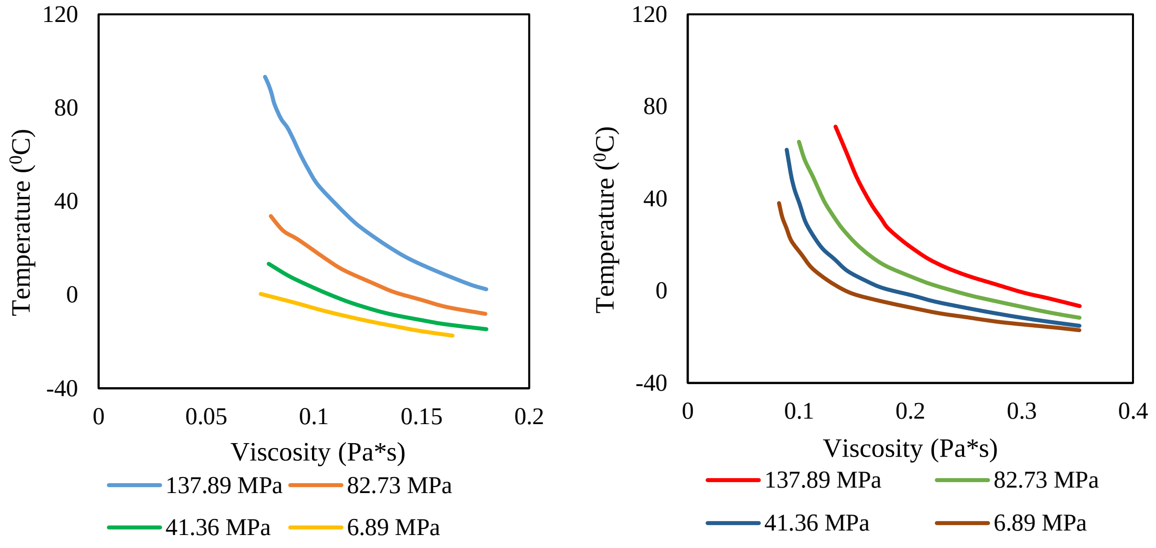


Figure 1.7. Effect of temperature on the equivalent viscosity of drilling Fluid A and B are given in the left and right respectively. [10]

For the designed invert emulsion drilling fluid sample D with 2.26 sg drilling fluid, the shape of the equivalent viscosity versus temperature is different. At 121 ^{0}C, mud's viscosity begins to increase after sharp decreasing, while this happens for sample E at 162 ^{0}C however, generally equivalent viscosity versus temperature trends are matching.

A water based mud which is considered sample F was prepared without any weighting material and its apparent viscosity and equivalent viscosity measurements were taken. The apparent viscosity increases with increasing temperature up to 121 ^{0}C and then at 149 ^{0}F it begins to decrease, where at this temperature decrease in viscosity depends on the composition of the mud and shear rate. However, beyond this temperature higher values of the equivalent viscosities are obtained with an increase in the temperature up to 176.67 ^{0}C decrease in the viscosity is observed when the temperature is increased after 176 ^{0}C, although viscosity values are higher at higher temperatures [10]. Beyond 121 ^{0}C, an increase in the viscosity at a constant temperature in higher pressures is due to pressure increase due to the gelling effects of clays.

Afterwards, fluid F is treated with chemical mixture and as a result, much lower values for the both apparent and equivalent viscosities are observed. High pressure does not have any effect on the viscosity at low temperatures, however at high temperatures the difference is obvious. In sample fluid H, which has 2.2 sg density, equivalent viscosity values are not affected to the same degree by pressure as it did in invert emulsion fluids. At 26.67 ^{0}C, pressure does not have an effect on equivalent viscosity, while in high temperatures, an increase in the equivalent viscosity is observed with increase in pressure.

1.3 Chapter Summary

The chapter is based on analysis and results obtained from case studies that have been carried out, it has been observed that how wellbore instability issues can be solved by using proper techniques to prevent ECD become a problem for the wellbore. While modelling drilling fluids for the well, importance of the offset wells in the field can prevent any possible losses of drilling fluids to the formation, fracturing formation, hole collapse and any other problems.

CHAPTER 2. RESEARCH METHODOLOGY

2.1 Strategy of Research

In this chapter, the methodology of the research is discussed and information about simulation, data is used for the simulation is presented. In order to show ECD optimization in the wellbore, based on the literature review and as a result of the research, two wells have been chosen, where by using data of this wellbore simulations are carried out. ECD analyses are carried out based on casing running and cementing simulations in Drillbench Dynamic Drilling Simulation Software in each of wellbores. During casing running, surge analysis, then drilling fluid conditioning and finally cementing simulations are carried out. After obtaining results from both of the existing wells, the results are compared and feasibility of changes in the well is discussed. The strategy of the software analysis is presented in the following Figure 2.1. [17]..

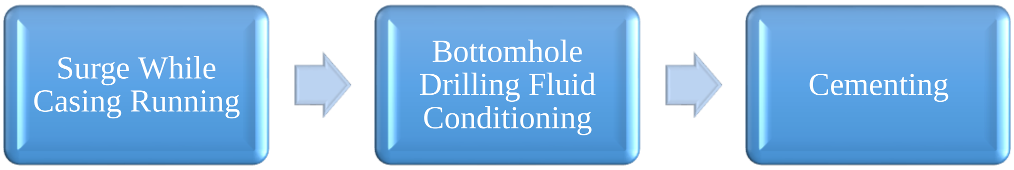


Figure 2.1. Simulation Procedure Sequence

2.2 Simulation Content

In the North Sea well reservoir section well ID is 216 mm and it is cased with 178 mm OD liner, after which 152 mm OD open hole come. In this kinds of wells single tubing completion case is used where there is not tubing size restriction [11]. On the other hand, when this well is intended to be completed with dual tubing completion and with cased reservoir section, where 2 tubing is run to the reservoir section, 178 mm OD liner allows maximum tubing size to be 38 mm OD [12]. Authors prove that this size of tubing causes huge frictional losses in the tubing, which causes several production problem [13]. That's why for dual tubing completion design larger tubing size is required, which can be achieved by enlarging hole size in the reservoir section. This can be accomplished by setting 244 mm OD casing to the reservoir section. However, putting 244 mm casing string to the reservoir section changes entire well design.

In the simulations, firstly in 2 wells, feasibility of changing well designs is investigated in terms of hydraulics in the wellbore and new mud weights, new cement weights are designed where their rheology is analysed. Hence, 406 mm casing section, 340 mm and 244 mm full string running and cementing simulations will be carried out. Because of change in casing design itself, new casing setting depths also prepared based on Pore Pressure Fracture Gradient Curves. Then results from both of the wells are compared and the final decision about feasibility changing the design of these wells are presented.

2.3 Simulation Material

In order to find a well design with full of data, extensive research has been carried out and a number of well data in Norwegian Petroleum Directorate Database have been searched. As a result data of 2 wells that were drilled in Gullfaks field have been analysed and they are considered for current simulation and analysis. 34/10-1, 34/10-3 wells are chosen and in the Figure 2.2 and Figure 2.3, Pore Pressure Fracture Gradient (PPFG) of 34/10-1, 34/10-3 are presented respectively [14].

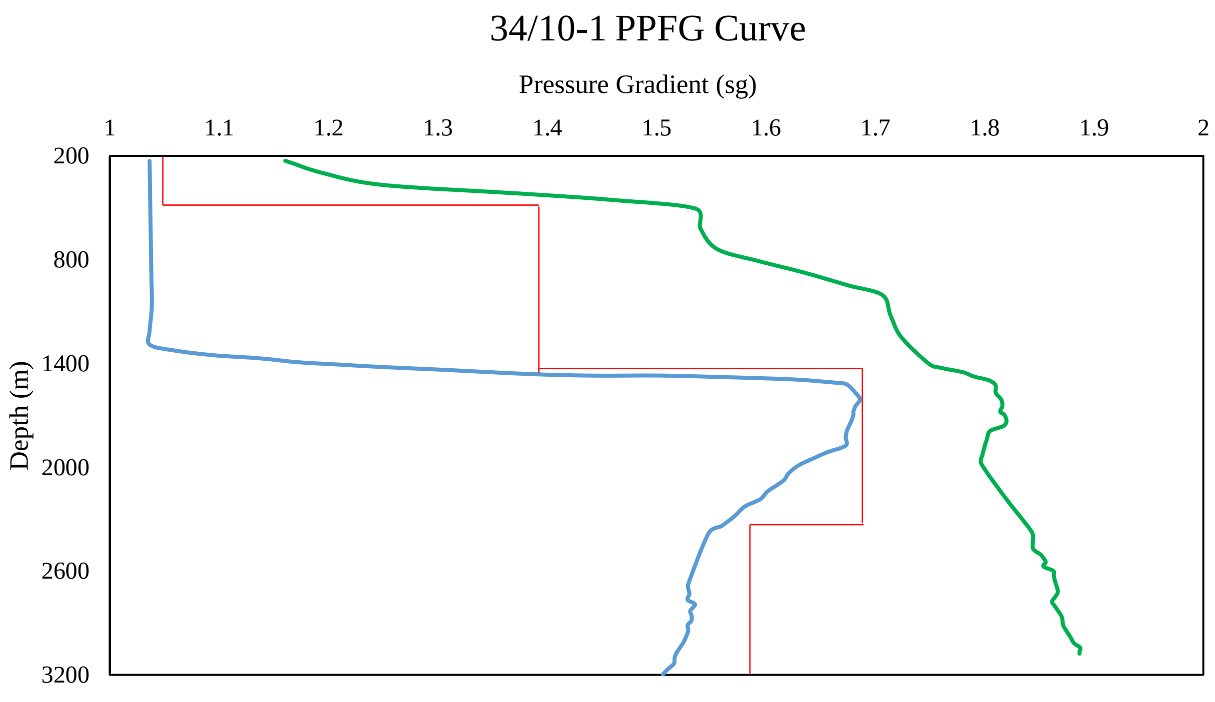


Figure 2.2. Pore Pressure Fracture Gradient Curve of 34/10-1 [15]

In the Figure 2.2 and Figure 2.3 blue curve presents formation pore pressure and the green curve presents formation fracture strength. As mentioned in literature review this curves are presented in specific gravity units, where their values are converted from MPa. On the other hand red horizontal lines present, planned casing setting depths, while red vertical lines present mud weights are chosen for the casing sections in both of the 34/10-1 and 34/10-3.

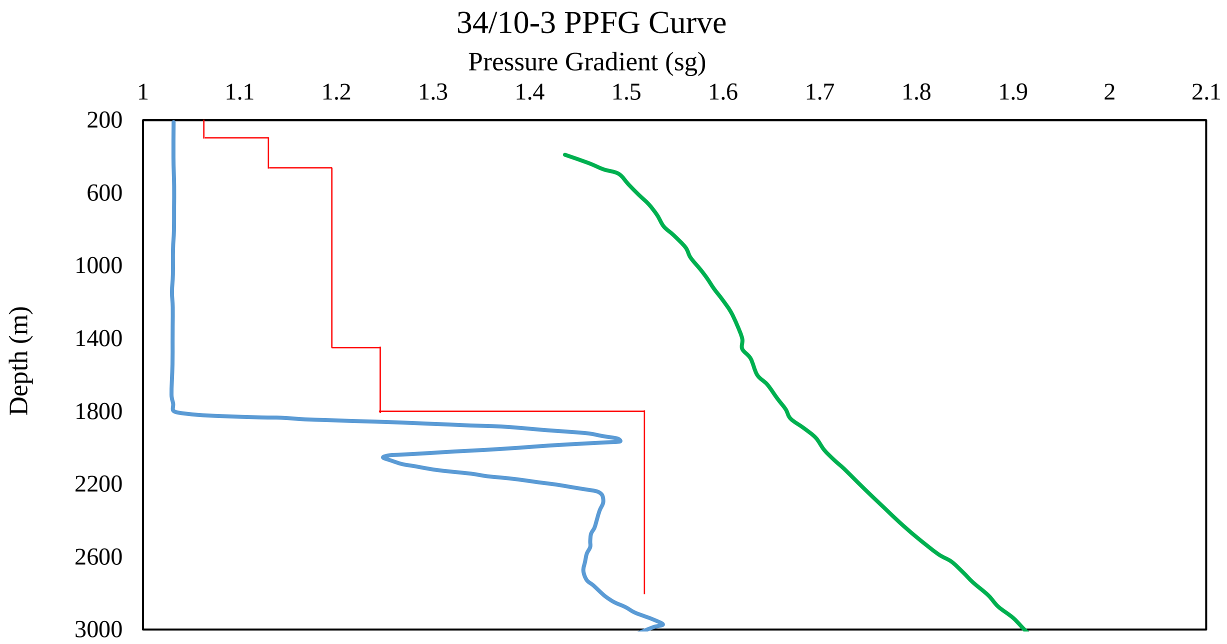


Figure 2.3. Pore Pressure Fracture Gradient Curve of 34/10-3 [11]

For the 34/10-1, Pore Pressure and Fracture Gradient Graph was obtained in pressure versus depth, however for determining mud weight and casing setting depth, it has been converted to the pressure gradient values. As can be seen from the Figure 2.2 and Figure 2.3, these PPFG curves are completely different, hence for well 34/10-1 mud window is very small, so making changes to this well will be difficult. On the other, 34/10-3 has wide mud window, which enables to make changes in the well structure. It is important to mention that these wells are exploration wells, so in exploration wells, it is common to have different well designs, as there are not any previously drilled offset wells in the field. That's why by using these wells their data analysed and future wells in the field are drilled with reference to them. So, a further change to this wells is commonly accepted [16]. According to the plan, as mentioned before, well casing design will be changed and feasibility of this change in terms of hydraulics will be examined. The new well design based on the PPFG of the wells.

During the simulation drilling mud that used is oil based mud and this mud design has a number of advantages, which are presented in the previous chapter [3]. The cement design has also prepared for different hole sections and slurry property is prepared. Drilling mud and cement are simulated in the software in order to determine hydraulic boundaries and testing feasibility of well design change. In the Gullfaks field 34/10-3 well, casing and hole design is as following:

Table 2.1. Gullfaks Field 34/10-1 and 34/10-3 Hole Geometry

Well	Casing Type	Hole size OD	Hole Depth	Casing Size OD	Casing Depth
34/10-1	Conductor	914 mm	211 m	762 mm	211 m
	Surface	660 mm	475 m	508 mm	475 m
	Intermediate	445 mm	1550 m	340 mm	1550 m
	Production Casing	318 mm	2200 m	244 mm	2200 m
	Open Hole	216 mm	3000 m	-	-
34/10-3	Conductor	914 mm	250 m	762 mm	250 m
	Surface	660 mm	550 m	508 mm	550 m
	Intermediate	445 mm	1470 m	340 mm	1470 m
	Production Casing	318 mm	1805 m	244 mm	1805 m
	Production Liner	216 mm	2250 m	178 mm	2250 m
	Open Hole	152 mm	TD	-	-

2.4 Software Input

2.4.1 Casing Setting Depth

Based on PPFG curves, new casing setting depth is proposed, where at the same time mud weights were also estimated for each new hole section. Thus, casing has to be set to such a depth that maximum pressure that is going to be encountered in the next hole section should be smaller than fracture gradient of the casing shoe depth formation. The highest pressure that will be encountered in the open hole section will occur when circulating out a gas influx [1]. In the 34/10-3 casing setting depths are not changed, however casing size itself changed, while in 34/10-1 both their sizes and setting depth are changed. According to plan, in the new well design, 406 mm casing will be added to the design, it will be followed by 340 mm full string section. Then after 340 mm casing section, 244 mm casing will be run to TD. The depth of proposed casing strings and their setting depth are presented in Table 2.2 for 34/10-1 and 34/10-3.

Table 2.2. Casing Setting Depths

Casing	Setting Depth 34/10-1	Setting Depth 34/10-3
406 mm	1450 m	1470 m
340 mm	2300 m	1840 m
244 mm	2800 m	2800 m

2.4.2 Mud Properties

Mud weight in the well is also determined according to the PPFG curve where during drilling and casing setting operations in particular hole section, drilling fluid ECD should be between pore pressure and fracture gradient. Thus, if it exceeds fracture gradient then losses will occur and there will be huge wellbore stability problems, on the other hand if mud ECD falls below pore pressure then in the well kick will occur [3]. That's why each hole section has to be drilled and cased with different mud weight where mud weight does not change in one particular section. According to the plan, mud weights used for the drilling and casing hole section are summarized in the following Table 2.3. For consistency with Pressure Gradient and to avoid possible misunderstanding mud density is presented in Specific Gravity:

Table 2.3. Mud Weights in Casing Sections

Hole Size	Casing Size	Mud Weight for 34/10-1	Mud Weight for 34/10-3
660 mm	406 mm	1.39 sg	1.18 sg
445 mm	340 mm	1.68 sg	1.25 sg
318 mm	244 mm	1.58 sg	1.53 sg

Rheology of the mud becomes different in each operation in the wellbore. Hence, while running casing into the wellbore, mud rheology is different from mud rheology and weight that is used for the mud conditioning prior to cementing. So it is desirable to reduce the drilling mud density without compromising well control. During the simulation possibility of decreasing mud weight during the mud conditioning is investigated and where it is possible to decrease mud weight, this technique is applied. During mud conditioning, mud weight is decreased and also rheology is changed. The purpose of doing this is to prepare hole for the cementing operations and clean annulus from gelled and hydrated mud. This procedure will be also simulated in Drillbench Software, where volumetric rates will be determined for this particular process [5].

2.4.3 Cement Properties

As mentioned before, cement weight is determined based on the offset well cement designs in the similar hole depth cementing design [14]. These designs are changed for this particular well sections according to the following rule: industry-accepted practices considers that there should be at least 10% hierarchies in densities and rheology of displaced and displacing fluids [5]. So it means that in the cementing procedure, density of cement has to be at least 10% higher than density of displacing fluid such as spacer. This helps to better displacement of fluids and successful cement job in the casing. Moreover, when this hierarchy rule obeyed, no channelling occurs, on the other hand, better cement bond will happen.

During the simulation process, flushers and spacers will be used. The purpose of using these fluids to separate incompatible fluids such as drilling mud and cement. Base oil is type flusher is going to be used in the cementing simulation and they enter hole in low rates but in turbulent flow, which basically helps to clean wellbore from drilling mud gels, which are left from drilling procedure. Flushers have significantly low density and in this project density of base oil which used as a flusher is 0.82 sg and base oil is displaced after the drilling mud. However, spacer which has the similar purpose as flushers are pumped ahead of cement and its density will change during cement displacement of different hole sections. During the cementing of the casing strings conventional Class G cement and other cement types will be used.

2.4.4 Drillbench Software

The simulations are carried out Schlumberger Drillbench Dynamic Drilling Simulation Software and dynamic hydraulic effects in the wellbore are investigated. By help of this software it is possible to reduce the difficulty of the planning stage which will enhance drilling engineers' ability of making chooses. Thus, this software has been especially created in order to provide an ability to drilling engineers for predicting and understanding the hydraulic barriers, ECD, and manage them. By using this software, all mentioned simulations above are carried out and realistic results are obtained. This software delivers us arrangements of graphical results as well as accurate modelling which enables us for simulating before drilling. All before mentioned applications of the software are vital, that is to say especially in the drilling windows are small so design margins are not affordable. As it is very well known that in the future most of the fields will be unconventionally drilled due to their complicated characteristics so the limits between pore pressure boundary and fracture pressure edge will be even lower [17].

2.5 Chapter Summary

This chapter provides information on the design and format of the simulations. As mentioned before main simulation will be carried out for 3 different wellbore sections, where in each section surge analysis, bottomhole mud conditioning and finally cementing simulation are carried out.

Moreover, in the chapter, all the inputs to software are described and also information about software is presented. In the next chapter, simulation itself along with its results are be presented.

CHAPTER 3. SOFTWARE ANALYSIS AND SIMULATION RESULTS

In this chapter, for both of the wells simulations and their results carried out in the Drillbench Software are presented. Results are presented according to the sections of the wells and results of 34/10-1 and 34/10-3 are compared, feasibility of the carrying out particular stage is discussed. All the graphs obtained from software are converted to the Excel.

3.1 Hole Section 508 mm

As mentioned in Chapter 3, after 508 mm surface casing, 406 mm casing is utilized in both of the wells. Planned depth for 406 mm casing shoe is 1470m for 34/10-3 and for the 34/10-1 1450 m. As can be seen from the Figure 2.2 and Figure 2.3, the mud window in the given depths are wide, thus running and cementing the string is possible.

3.1.1 Surge Analysis of 406 mm Casing

The Surge analysis presents information about running speeds of the string. The analysis is performed in order to determine at what maximum running speed of casing can be achieved without fracturing weakest points open hole. In most cases the weakest point of the formation is previous casing shoe, unless otherwise is mentioned. Thus, ECD is caused by tripping in of casing in open hole, should not exceed formation fracture gradient. Without knowing this values, it is not possible to carry out casing running operations safely. In 34/10-1 well while casing running is initiated, drilling mud is in the hole has 1.39 sg density and its plastic viscosity is 0.03 Pa·s, yield point of 11.97 Pa and Fann reading input at 3 rpm is 6.22 Pa. While for the 34/10-3, density is 1.18 sg and other rheology properties are the same. On the other hand, as mud forms gel when it is stable in the wellbore, in the expert input section of the software it is also inserted, however gel model can be activated and deactivated for particular simulation section. Hence, gel forms 7 Pa in 10 seconds, in 600 seconds it is 11 Pa. In both of the wells, there is around 20 m space below the casing shoe which prevents casing hit the bottom of hole during surge simulation. In 34/10-1, when gel model is activated for 340 mm casing, it is only possible to run casing at the speed of 0.067 m/s, however without gel model this speed can be increased to 0.2 m/s. Conversely, in 34/10-3 well gel model does not create a problem for wellbore stability, where in both cases it is possible to run casing at 0.2 m/s, so running speed is not limited. In Figure 3.1, results of surge analysis for 34/10-1 with and without gel model at the point of interest is presented.

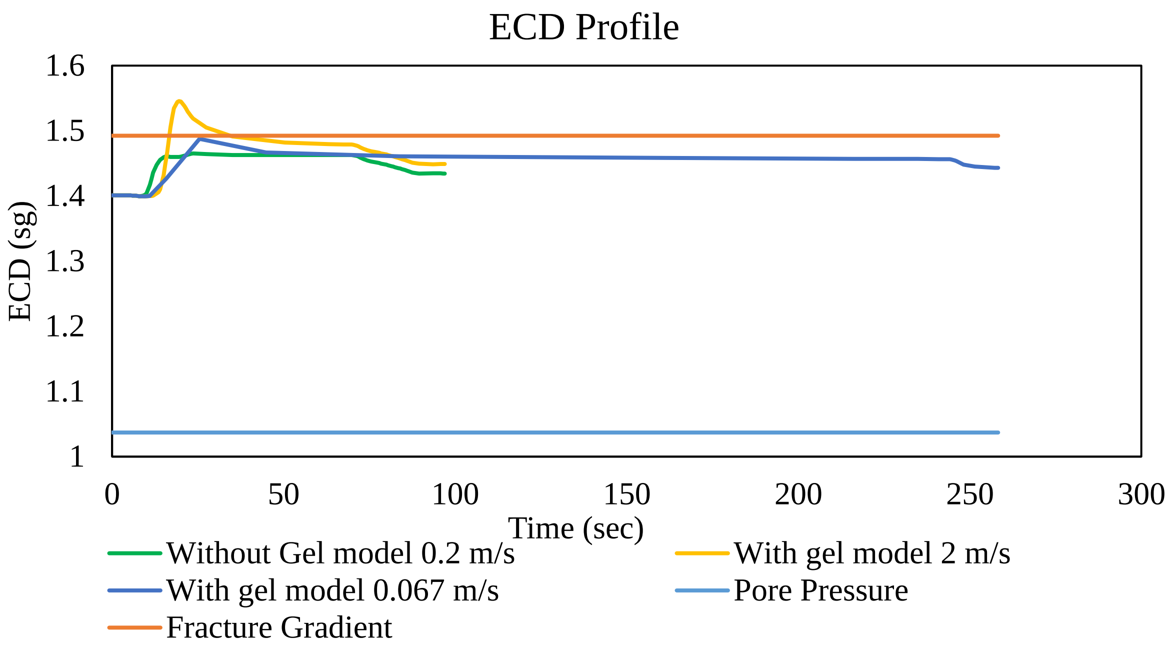


Figure 3.1. ECD Simulation in 406 mm casing running in 34/10-1 well with and without gel model.

The point of interest is the weakest point in the open hole section and it has been previously mentioned that the weakest point in the open hole section is previous casing shoe. In this particular case, previous casing shoe is the shoe of 508 mm surface casing, so profile above is given at the depth of 660 m. As can be seen from Figure above, although tripping velocity is 3 times lower with gel model, still ECD is high and also it takes very long time to run string al lower speed.

3.1.2 Mud Conditioning on 406 mm Casing

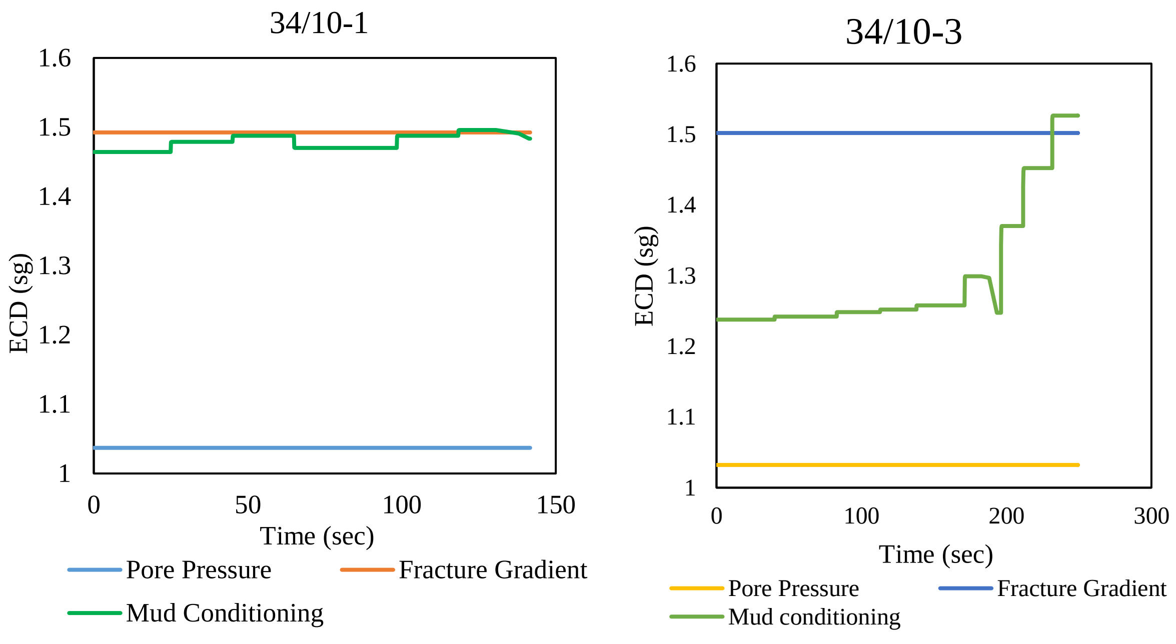
Circulation before cementing is very necessary as some of the mud properties are designed for the drilling operations while they are not efficient for mud displacement during cementing. While circulation mud density and its rheological properties are changed. Conditioning and circulating mud helps hole cleaning from cuttings, the gelled and dehydrated mud that is trapped in washouts; on the narrow side of an eccentric annulus is eroded, so well prepared for the better cement displacement. The point which makes this mud conditioning and circulation operation challenging is small annular clearance. As mentioned before, during mud conditioning it is preferred to decrease mud weight and its rheology. This enables to circulate much higher flow rates, where ECD does not increase. But it has to be done in a way that, well integrity should not be compromised. Thus, mud weight should not be taken below pore pressure, otherwise well control issues can occur.

In 34/10-1, mud weight for the drilling operation was considered as 1.39 sg and this was minimum possible mud weight to avoid kick. So prior to cementing operation, in 34/10-1 well it is not possible to decrease mud weight itself. However, mud rheology can be changed for mud conditioning purpose, where it is still possible to increase flow rates. This change is also going to be the same for the rheology of the mud in 340 mm and 244 mm casing sections. Hence, change in the mud rheology is presented in the following Table 3.1.

Table 3.1. Mud Rheology

Rheological Property	Property pre-conditioned mud	Property post-conditioned mud
Plastic Viscosity (Pa·s)	0.032	0.03
Yield Point (Pa)	11.97	9.58
Fann Reading 3 rpm (Pa)	6.22	5.27

On the other hand, in 34/10-3, mud weight for drilling was taken 1.18 sg and it is much higher than pore pressure limit. That's why decreasing mud weight in this particular section is possible and still no well stability issues are encountered. In the Figure below, results from both 34/10-1 and 34/10-3 wells in 508mm casing section are presented.



(a) (b)

Figure 3.2. ECD at mud conditioning of 406 mm casing in 34/10-1 and 34/10-3 at 508 mm casing shoe.

As can be seen from both of the plots during the mud conditioning, mud flow rates are increased with increments, hence in 30/10-1 well, initially preconditioned mud circulated with 0.031 m^3/s, 0.053 m^3/s and 0.066 m^3/s, then it is followed by conditioned mud with 0.039 m^3/s, 0.066 m^3/s, 0.079 m^3/s. Fracture gradient at the point of interest is 1.49 sg and 0.066 m^3/s, pre-conditioned mud, the limit is reached, without fracturing formation. So, it preferred to circulate at lower rates than 0.066 m^3/s. On the other hand, when lower rheology fluid behaviour is closely analysed, it is possible to say that at 0.066 m^3/s flow rate ECD is lower than the one with pre-conditioned mud. The simulation also has been carried out in the 34/10-3 well and its limits were also tested. In this case, ECD of circulation only exceeds if mud is circulated at 0.22 m^3/s, however it is important to say that such a big flow rate are not required for the mud conditioning. It is possible to say that for both of the wells, it was possible to circulate mud with higher flow rates and make wellbore ready for the next cementing operation. Moreover, in all of the cases above, gel model was activated where it further makes challenges and at this particular stage of the drilling process.

3.1.3 Cementing of 406 mm casing

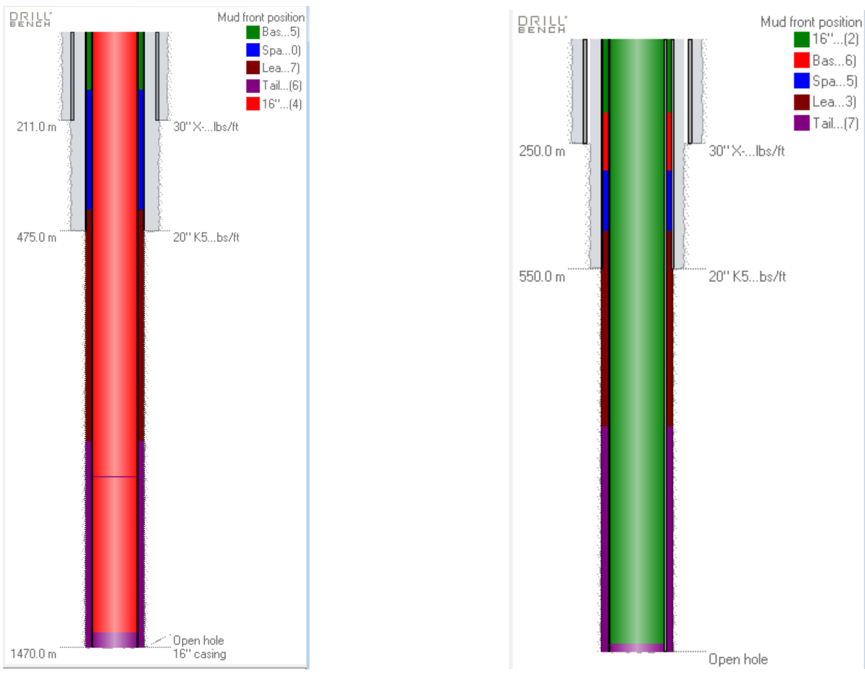
After circulation and conditioning mud is finished, wellbore and casing itself are ready to be cemented. During cement weight determination, as cited before, 10% rule has been taken into account hence, there has to be 10% difference between displacing and displaced fluids. Also, for cement program in each of the wells, spacers and base oil have been added for previously mentioned purposes. The main purpose in the cementing is that hydraulic seal or hydraulic overlay between two casings has to be achieved between two casings [13]. In the Table 3.2 cement programs created for the 34/10-1 and 34/10-3 are presented:

Table 3.2. Cementing Program for 406 mm Casing

Well	Fluid	Density (sg)	Flow rate (m^3/s)	Volume (m^3)	Temperature (^0C)
34/10-1	406 mm cementing mud	1.39	0.01325	1.59	15
	Base Oil	0.82	0.02385	7.949	15
	Spacer	1.18	0.01855	15.899	15
	Lead Cement	1.60	0.0159	39.747	15
	Tail Cement	1.80	0.0106	39.747	15
	406 mm cementing mud	1.39	0.0106	164.962	15

Well	Fluid	Density (sg)	Flow rate (m^3/s)	Volume (m^3)	Temperature (^0C)
34/10-3	406 mm cementing mud	1.14	0.03975	31.797	15
	Base Oil	0.82	0.053	7.949	15
	Spacer	1.10	0.053	7.949	15
	Lead Cement	1.45	0.0265	31.797	15
	Tail Cement	1.65	0.0265	39.747	15
	406 mm cementing mud	1.14	0.053	166.937	15

As can be seen from the cementing program, there is at least 10% difference between lead and tail cement in both cases. The sequence of the program given above is created according to the data obtained from literature review and close examination of the offset wells in Gullfaks field [14]. In order to check whether cement has reached to the planned depth or not in the Drillbench Software, mud front position versus depth is plotted and also mud front position is illustrated in the well structure in Figure 3.3.



(a) (b)

Figure 3.3. Cementing schematic of 34/10-1 and 34/10-3 wells after cementing of 406 mm casing

Because of larger annular clearance between 508 mm hole, 508 mm surface casing and 406 mm casing and also as a result of larger mud window between 508 mm casing shoe and TD of open hole, it was easy to run casing, condition mud and cement casing in its place without creating and having wellbore stability and well control issues. Hence, running and cementing 406 mm casing is hydraulically doable.

3.2 Hole Section 445 mm

The same procedures for the 508 mm hole section are applied for the 445 mm hole section, however, this particular section is much more challenging for the both of the wells. As can be seen from Figure 3.2 and 3.3, for this particular section, mud window is not as large as it was for the 445 mm section. Moreover, casing size is 340 mm and hole geometry is much smaller, where initially 406 mm casing and then it is followed by 445 mm open hole. This means while running casing, mud conditioning and cementing operations, there is going to be big frictional losses in the hole and because of it, if ECD is not very well controlled then hole stability issues can occur. Planned depth for 340 mm casing in 34/10-1 well is chosen to be 2300 m, so open hole length will be 850 m, while in the 34/10-3 well, open hole depth will be 370 m. This is because as mentioned in the previous chapter, 34/10-3 well, casing depths will not be changed, only sizes of the casings are different.

3.2.1 Surge Analysis of 340 mm Casing

In 34/10-3 well, 340 mm intermediate casing is run into the hole at the 0.2 m/s tripping velocity and this speed maximum running speed in the rig. Beyond this speed generally running is not carried out. Drilling fluid in the hole, while running initiated has 1.5 sg density and in the given parameters, it is possible to run casing to the hole without causing any wellbore stability problem. Maximum pressure caused by mud flow in the casing shoe of 406 mm casing is 21.5 MPa and this value 1.9 MPa smaller than fracture strength of the formation at 1470 m depth. So, running 340 mm casing at this speed is safe.

On the other hand, in well 34/10-1 things are very different. Hence, in this section mud window is very small and so it is very important to run casing at very low speed. In addition, for the surge analysis, Drillbench Software offers unique property it is still possible to optimize ECD created in this section. Hence, as can be seen from the Figure below, acceleration and minimum and maximum string velocities are defined.

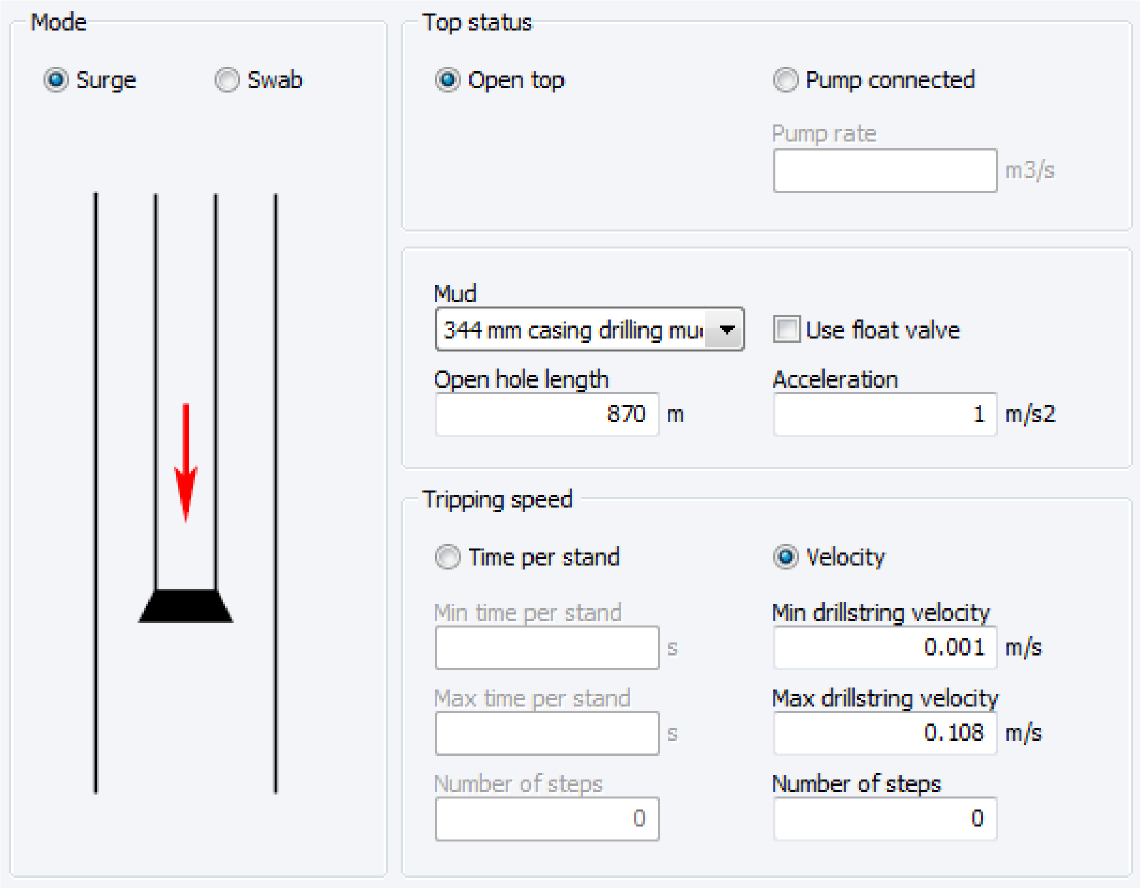


Figure 3.4. Surge Analysis Window in Drillbench Software

It means that pipe should enter the hole, as low speed as possible, where initial speed has to be very low. Then, by acceleration mentioned above increases running speed gradually. In this particular case, minimum pipe velocity is $5.55 \cdot 10^{-4}$ m/s however, as can be seen from the Figure above software takes this number as 0.001 m/s. That's why for simulation itself pipe velocity is entered in 2 m/hr unit where it is possible to simulate actual running. With maximum running speed of 0.108 m/s and 1 m/s^2 acceleration, it is possible to run casing to TD without fracturing formation. However, other possibilities were also examined, hence at 3 m/hr minimum running speed, fracture gradient at 1450 m exceeded around 0.25 MPa, which actually is not small value. On the other hand, if gel model is switched off, then it is possible to run casing at 0.2 m/s maximum speed and 0.01 m/s minimum speed. In Figure 3.5 (a), surge model of 340 mm casing with gel model on the case, on the other hand in Figure 3.5 (b), surge model with gel model off case have been presented.

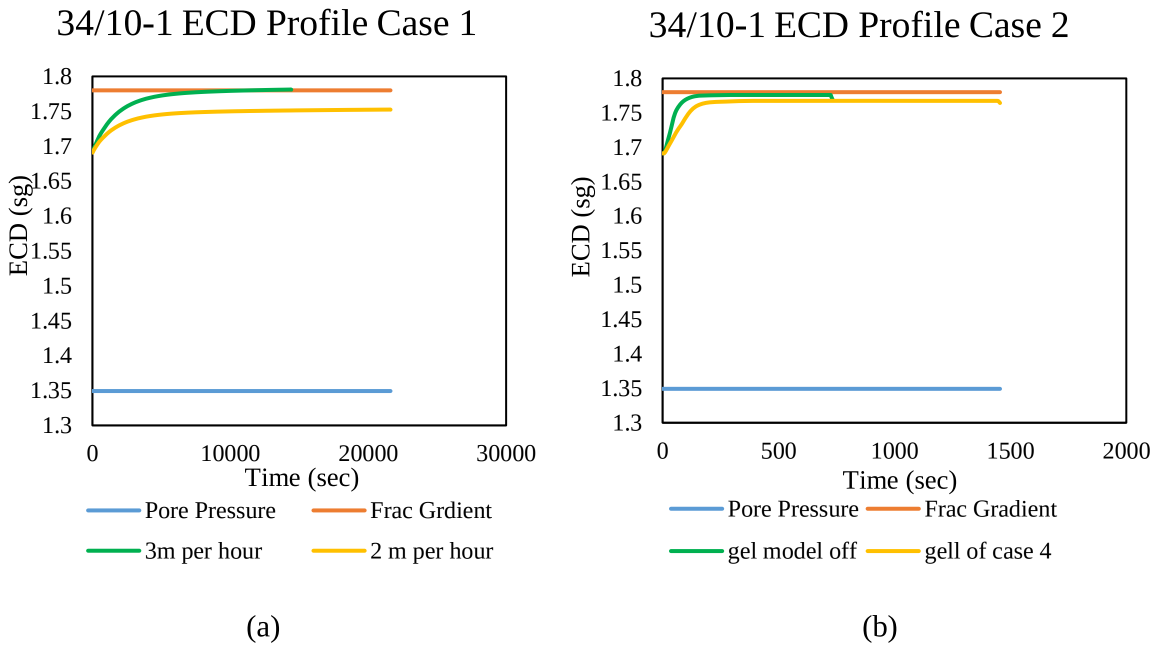


Figure 3.5. ECD Profile at previous casing shoe while running 340 mm casing (a) with gel model (b) without gel model.

As can be seen from the Figure 3.5 (a) while running casing at minimum 3 m/hr speed, then fracture occurs, while at the speed of 2 m/hr fracture has not been obtained. On the other hand, in the case where gel model is switched off, it is possible to run this casing 0.2 m/s speed. So it is possible to conclude that, running this casing without fracturing formation is possible, even if gel model is on.

3.2.2 Mud Conditioning on 340 mm Casing

After successfully being able to run casing to the bottom of the open hole section, next objective is to clean annulus behind 340 mm casing from cutting remaining and gelled mud. Cleaning will improve next stage cementing. As cited in the 3.1.2 section, at this stage changing mud rheology is considered, where if it is possible mud weight is going to be decreased. During the conditioning mud in 34/10-1 well because of well control issues, mud weight could not be decreased below 1.68 sg in 34/10-1. However, its plastic viscosity and yield point decreased significantly. In this case, it important to mention that, as the previous case, because of small annular clearance it is extremely difficult to condition mud. As can be seen from Table 3.3 flow rates during circulation is very low in both pre-conditioned mud and post conditioned mud. Also in the Table, during the simulation, how much formation strength was exceeded in each case were presented.

Table 3.3. 34/10-1 well Drilling Fluid Conditioning mud sequence

Drilling Fluid	Density sg	Flow rate (m^3/s)	Volume (m^3)	Pressure Difference (kPa)
Pre Conditioning mud	1.68	0.0015	63.59	-110
Pre Conditioning mud	1.68	0.003	95.39	53
Pre Conditioning mud	1.68	0.004	63.59	194
Post Conditioning mud	1.68	0.005	63.59	-98
Post Conditioning mud	1.68	0.007	95.39	1.6
Post Conditioning mud	1.68	0.008	63.59	97

It is clear from the Table above that, with pre-conditioned mud it is possible to circulate mud at maximum flow rate of 0.0015 m^3/s without fracturing formation and in this case pressure of the mud is 110 kPa smaller than fracture gradient of the formation. As mud weight for the drilling operations was taken as low as possible because of that reason, for the mud conditioning purposes mud weight could not be decreased. However after mud is conditioned, where its rheology has decreased, it is possible to circulate mud at 0.005 m^3/s without causing wellbore stability issues.

In 34/10-3, things are much better, hence because of the bigger mud window, although annular clearance is small, during mud conditioning no fracture detected even at very high mud flow rates. Another reason for this situation is that in 34/10-3 well not only mud rheology, mud also its density decreased without compromising well control. Thus, pre-conditioned mud has 1.25 sg density, where mud circulated at 0.0424 m^3/s and conditioned mud has a density of 1.2 sg density and it is possible to circulate it 0.0636 m3/s flow rate. It is clear from values, that in 34/10-3, the flow rate of drilling fluid is 12 times bigger than 34/10-1, which indicates 34/10-3 has very large mud window.

3.2.3 Cementing of 340 mm Casing

As it was very difficult to carry out previous 2 operations on the 445 mm hole of the 34/10-1 well, cementing is also extremely challenging. On the other hand because of possessing larger mud window in the 34/10-3, cementing is going to be easy. However, because of these complications in 34/10-1, it very important to define proper cement weights for 34/10-1, which will enable to cement 340 mm section, without causing hole stability problems.

After a number of simulations were carried out for cementing of the 340 mm casing, where it was not possible to find an optimum cementing program for the casing. As a result of simulations, it is possible to say that, by using 10% fluid density difference rule in the cementing program cannot be obeyed. Hence, ECD caused by cementing is very big and in all cases fracture strength of the weakest point of the hole is exceeded and it is not practically possible to cement 340 mm casing by using the rule. However, there are variety cement types, where it is possible to have low-density high-performance cement [17]. By using this type of cement is possible to place cement slurry into the annulus. So, for this particular case, it has been considered to use this type of cement. Thus, by using this cement and violating rule mentioned above, it was possible to set casing and cement it in place. During cementing procedure, firstly, after the conditioned drilling mud, base oil with a density of 0.82 sg was pumped at the rate of 0.0026 m^3/s with total volume of 8 m^3. Then it is followed by spacer with a density of 1.34 sg, where after it leads cement with a density of 1.78 sg was pumped. Tail cement that used has 1.85 sg density and it is displaced to the annulus again with conditioned mud. In Figure 3.6, ECD profile of this cementing procedure is presented.

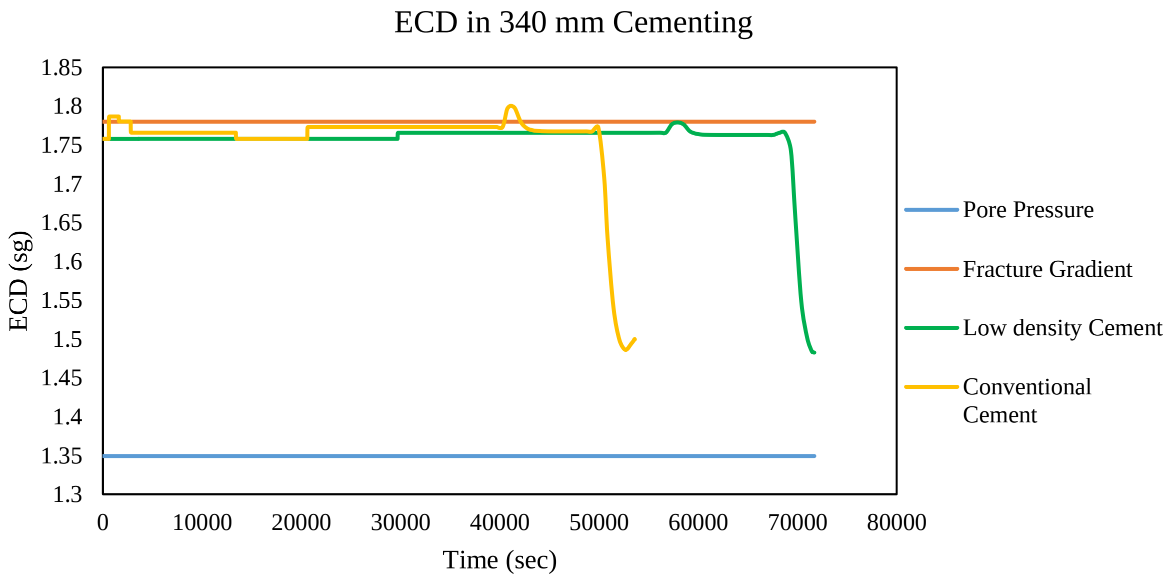


Figure 3.6. 34/10-1340 mm casing cementing

In the Figure above, 2 cementing procedures simulations are presented, where in the case of low-density slurry cementing was described above. In that case, fluid flow rates in the cement program were low and that's why cement displacement is not very good. On the other hand, conventional cement presented on the graph presents, the case where proper cement weight and flow rates have been used. However, this causes fracture of the formation at the weakest point of the open hole. In the 34/10-3, as there is larger mud window it was possible to cement 340 mm casing, with proper cement weight and flow rates. Hence, in this model, it is expected that good cementing can be achieved in the case of proper execution. In Figure 3.7, mud front position graph is presented.

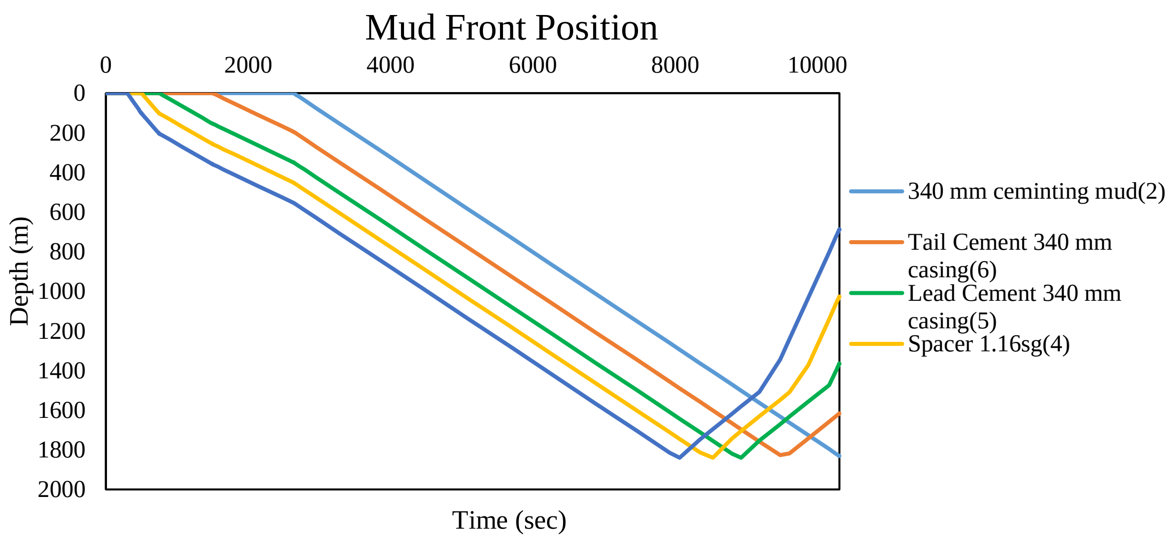


Figure 3.7. 34/10-3 Well 340 mm casing cementing Mud Front Position

This mud front position graph allows to clearly to see that lead and tail cement are reached to the planned depth during the cementing operation. Hence, no loss and fracture of the formation were encountered during cementing of the 340 mm casing. It is possible to state that although, with low density slurry cementing was carried out for 34/10-1 well 340 mm casing section, but there is not going to be proper cement displacement in the annulus. Hence, because of this low flow rates plus violating 10% hierarchy rule, there is going to be channelling and other cementing issues.

3.3 Hole Section 318 mm

After being able to finish operations on the 445 mm hole section, the final objective is to deliver cased 318 mm hole section. In this section of the hole, in both of the wells 244 mm casing will be run to the TD of the well. It is clear from Figure 2.2, mud window is large and from the original well structure itself, it is possible to say that carrying out following operations on the well is doable. On the other hand, in 34/10-3 well, mud window in PPFG curve is not as large as it was in 34/10-1, so special care has to be taken for this particular situation. According to the proposal, in 34/10-1 244 mm casing will be run until the 3000 m and it will be 2800 m in the 34/10-3 well.

3.3.1 Surge Analysis of 244 mm Casing

For the surge analysis, open hole length was taken 720 m in the 34/10-1 well and mud weight when casing string has entered to the hole is 1.58 sg. Initial velocity for the casing string was chosen as 0.1 m/s and it has a maximum velocity of 0.2 m/s and acceleration is 0.5m/s^2. The result of the surge analysis presents that at these running parameters which are generally considered as a maximum, 3.65 MPa margin exists until fracturing previous casing shoe. On the other hand, in 34/10-3 at the same running properties as 34/10-1 the margin is small. Hence, as can be seen from the Figure below, this margin is around 0.75 MPa at running speed of 0.2 m/s. This value is not dangerous limit and there is still margin for the error.

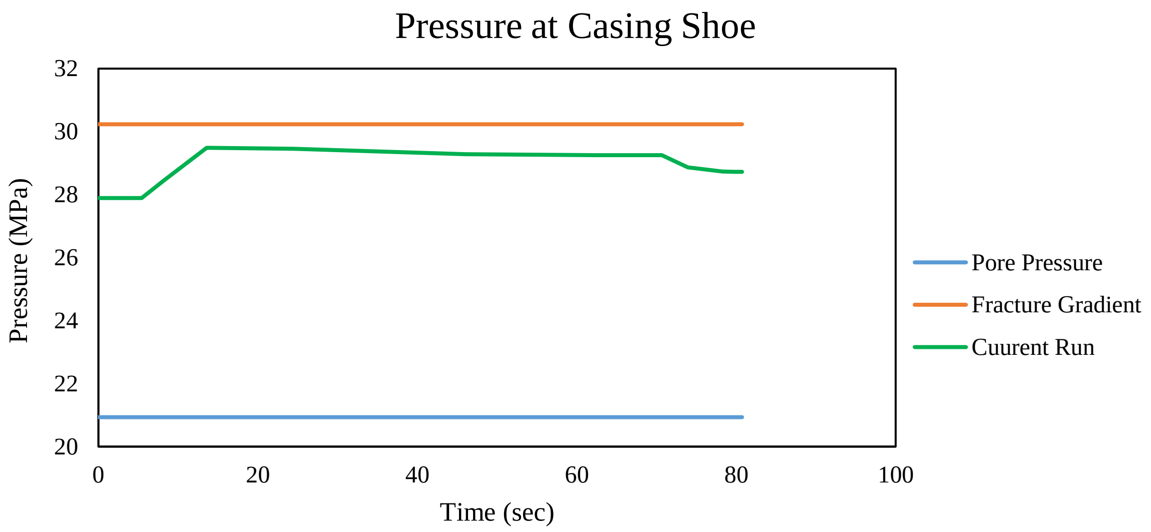


Figure 3.8. Pressure Profile in 34/10-3, while running 244 mm casing

Moreover, it is possible to say that, it is not necessary to run casing at 0.2 m/s speed, on the graph above just limit was presented. Thus, for the safe case, running speed can be decreased.

3.3.2 Mud Conditioning on 244 mm Casing

In the wellbore 508 mm and 445 mm wellbore sections, mud weight was chosen as a minimum because of smaller mud window in 34/10-1 well, that's why it was not possible to decrease mud weight during mud conditioning. However, in this hole section, mud weight was chosen 1.58sg and during the mud conditioning process, alongside mud rheology, mud weight is also decreased without compromising well control. Thus, post conditioned mud has 1.56 sg density in the well 34/10-1. On the other hand, in 34/10-3 well, pre-conditioned mud has a density of 1.53 sg and after conditioning its density is decreased to the 1.50 sg. Results from simulations show that even at higher drilling fluid flow rates fracture is not obtained in the wells. However, it is recommended to avoid flow rates above 0.053 m^3/s in both of the wells in order to avoid wellbore stability issues.

3.3.3 Cementing of 244 mm Casing

After being able to carry out mud conditioning process on both of the wells, the final stage is to be able to place cement the casings run into the hole. Thus, as it was carried out previous hole sections, cement weight and displacement program were established for this casings. Unlike 340 mm casing cementing in 34/10-1 well, cement flow rates and their weights are prepared in a way that cement displacement into the hole will be successful. Also, wellbore instability issues are avoided and there is room for error in 34/10-1 well. On the other hand, in 34/10-3 well, as can be seen from Figure 3.9 result of simulation reveals that during cementing of the 244 mm casing, maximum pressure at the depth of the 1840 m which is shoe of the 340 mm casing is 29.79 MPa, where at this point formation strength is 30.23 MPa.

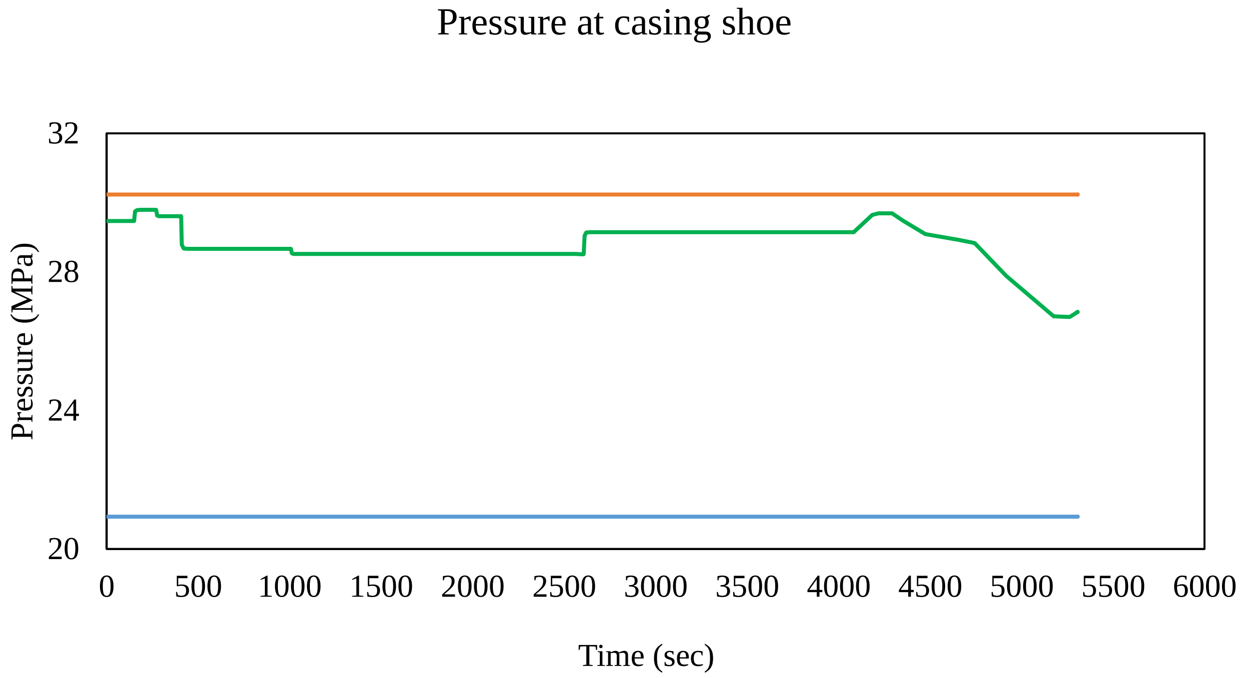


Figure 3.9. Pressure profile at the depth of 1840 m in 34/10-3 well while cementing

During cementing of the 244 mm casing section, firstly, hole section was filled with 1.5 sg post-conditioned mud and then it is displaced by base oil. After this spacer with 1.25 sg density at the rate of 0.058 m^3/s was pumped, where it is displaced by 1.75 sg lead cement at the rate of 0.021 m^3/s. Tail cement for this hole section was chosen to be 1.92 sg density at the rate of 0.016 m^3/s and this slurry was displaced to the hole with 1.5 sg density mud at a rate of 0.04 m^3/s.

During the cementing of the 244 mm casing, as fluids are circulated into the casing and the annulus, equivalent viscosity changes. As seen be seen from Figure 3.10, in the size of the of the annulus affects equivalent viscosity, in the plot, the annulus is filled with post conditioned mud and its original plastic viscosity is 0.03 Pa·s. However, in the annulus section, where annulus diameter is 314 mm viscosity is 0.059 Pa·s and in the section where annulus diameter increases to 318 mm due to open hole viscosity is 0.061 Pa·s. On the other hand, as all the displaced fluids are in the casing, wide variety equivalent viscosities exist in that section. Thus, in the casing where inner diameter is 244 mm, the equivalent viscosity of the mud 0.125 Pa·s. This proves how viscosity changes depending on the annular clearance size. In the Figure 3.10 below, equivalent viscosity versus time is presented, where green line presents 340 mm casing shoe.

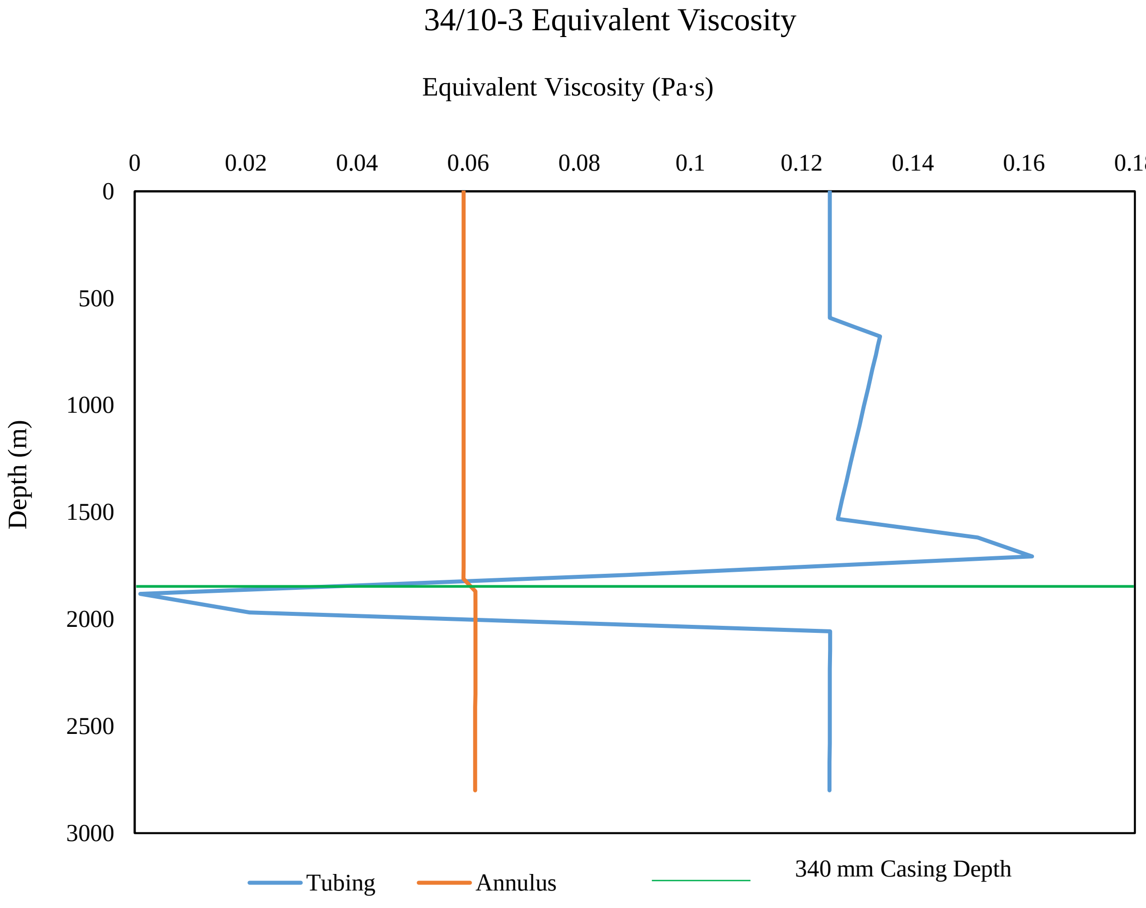


Figure 3.10. Equivalent viscosity versus depth in 34/10-3 during 244 mm casing cementing

3.4 Chapter Summary

The results obtained from the simulations carried out in different wellbore sections prove that changing wellbore design in 34/10-1 and 34/10-3 well is hydraulically possible. Hence, by carrying out simulations and inspecting wellbore stability in each of the steps in both wells demonstrate that well stability is under control and in the case of safe execution with the given proposal, wells can be delivered within expected conditions. In Figure below, both of the wells with their new structure is presented.

CHAPTER 4. DISCUSSION OF RESULTS

In this chapter obtained results from the simulations carried out several sections of the wellbore are discussed and they are analysed deeply. Optimization of the ECD in operations are presented and further recommendations are presented in the chapter.

4.1 Wellbore Sections

Firstly it is important to cite that, during the operations on the 406 mm casing, running casing and cementing it in place was possible due to controlled running speed, fluid rates during both mud conditioning and cementing in 34/10-1 well. Because of the big ECD caused by smaller mud window and also smaller annular size, running speed was taken low and fracturing of formation due to surge in the wellbore is mitigated. In original well structure, 406 mm casing was not presented, where immediately after 508 mm casing 340 mm casing is run, where there was a larger annulus, that’s why in this case size of annulus showed its effect in the ECD caused by surge and cementing of the smaller annulus. On the other hand in the 34/10-3, change of annular size did not affect make any threat to well stability because of larger window, so in both wells running and cementing 406 mm casing was hydraulically doable.

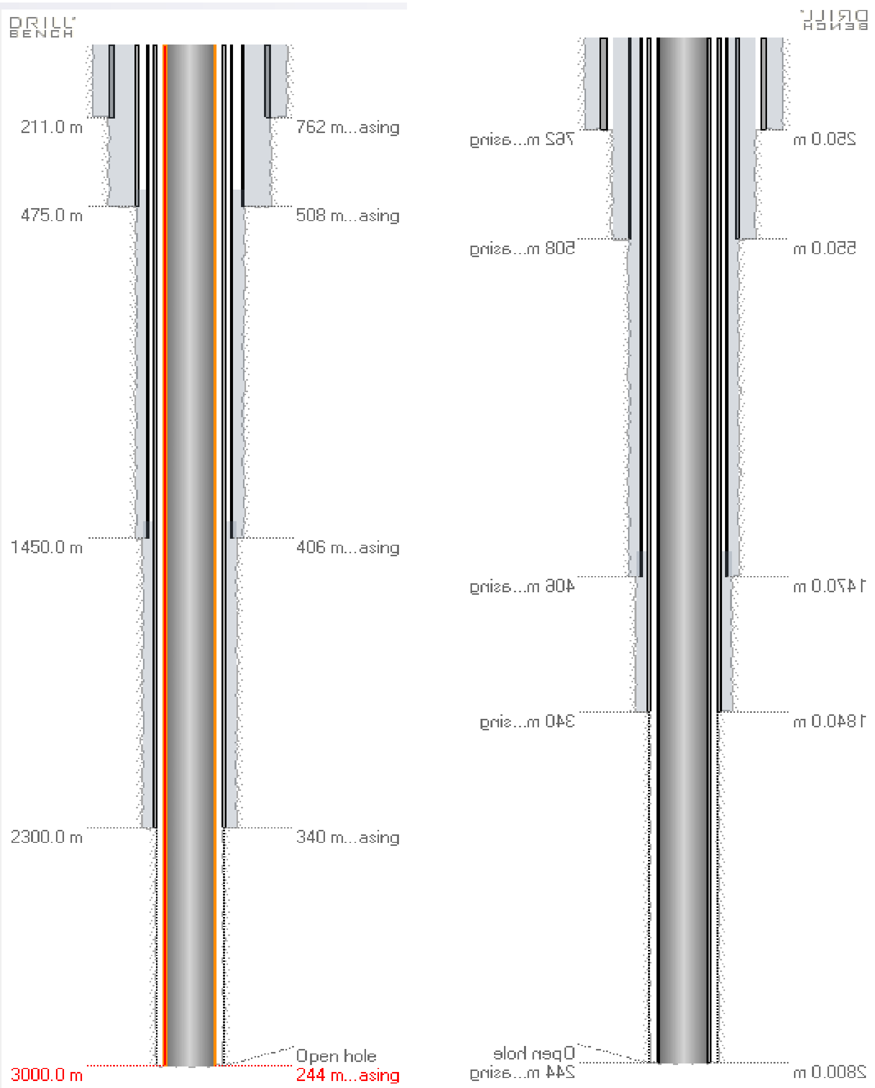


Figure 4.1. 34/10-1 and 34/10-3 well structure

However, things were a little bit complicated in the 34/10-

1 well from beginning to run it and cement it in place.

Thus, running speed checked very precisely and this section was the only section in the simulations where the effect of initial and maximum velocity played a significant role. In original well case, there was not any 340 mm casing section, where wellbore geometry was 508 mm casing until 475 m and 445 mm open hole. However, after addition of the 406 mm casing, annular clearance decreased significantly, where severe frictional losses were detected while running casing and cementing. However, by optimizing running speed it was possible to prevent surge happening in the wellbore. After being able to run casing to TD, mud conditioning was next challenge, hence mud was circulated at extremely low flow rates, but again it was hydraulically possible to change mud rheology and make wellbore ready for the cementing. During cementing, it was not possible to obey 10% density hierarchy rule, however a solution for this is industry accepted low density high compressive strength cement [17]. As a result, it is possible to state that despite many complications and smaller mud window in this section of the well, it was possible to run and cement 340 mm casing in 34/10-1 well. But, it is also very important to take into account that there is not any room for error in a given mud window. Thus, in this well PPFG diagram, fracture gradient was taken as a worst case scenario, where fracture gradient curve represents sandstone fracture strength. However, the formation is not always sandstone while drilling operation, thus, it can be shale or any other rock type, which can have much bigger fracture strength value. As a result, it is possible to emphasize that, although above it has been stated that there is not any margin for error, at some cases where there is 100% assurance for formation strength is much higher than the present value, it is acceptable to exceed fracture gradient. Unlike 34/10-1, for the 34/10-3, again, changing design of the well did not cause any well instability, hence it was perfectly possibly to run and cement casing with good simulation results.

However, only very small problem was encountered in 34/10-3 well, when 244 mm casing was run into the 318 mm hole, hence unexpectedly high ECD created when 244 mm casing entered to hole, however again as mentioned in 3.3.1 section, this is optimized by running at lower speeds. But overall, in both 34/10-1 and 34/10-3 wells, 244 mm casings were set safely and they were cemented in place securely. Another thing that assisted safe operations on 244 mm casing is that unlike 406 mm casing and 340 mm casing, annular clearance did not change for this section. Hence, in original wells 244 mm casing was run through the 340 mm casing and it did not change in new proposed design. In addition, in 34/10-1 well mud window was big in 318 mm open hole section, that’s why it was possible to do an operation on this wells.

4.2 Feasibility of Changing Well Design

There are a number of factors that affected the results obtained from simulation. However, there also some drawbacks behind the simulation results and they are clarified with the following bullet points.

- The primary factor that made the situation complicated in the wellbore is pore pressure fracture gradient curve. Hence, in 34/10-1 well mud window was narrow which caused problems in 340 mm casing operation. However, in 34/10-3 well, this window was large as result operations were carried out safely.
- Second reason was smaller annular clearance which caused very high ECD in wells, but it was possible to mitigate it by lower flow rates and lower running speeds.
- Gelling of the mud in the annulus also has an effect on the ECD, whereas it further decreased the annular size and causes obstacles for flow in the annulus. During the cementing gelling characteristics of the mud is minimized as it is not desirable for the cementing.
- For the casing running speed generally maximum speed in offshore platforms is taken as a 0.2m/s and during simulations running speed was taken as low as 0.016 m/s in order to prevent surge causing fracturing the casing shoe and open hole.
- Normal circulation rate for the mud conditioning process is 0.0318 m^3/s rate and during the simulations rates were reached to $0.053 \div 0.0636$ m^3/s rates. However, it was as low as $2.65 \cdot 10^{-3}$ m^3/s rates. Moreover, during the cementing, rates were taken were around $2.65 \cdot 10^{-3} \div 0.0212$ m^3/s. There are a number of problems that can be caused by low rates. Firstly, during the low rate circulation barite sagging can occur where because of it possible wellbore stability problems, such as stuck of the casing in the annulus can occur [2]. On the other hand, low cement displacement rate can cause mud channelling and poor quality cementing can occur [5].
- Another key thing is low mud rheology design for the cementing operations. This is because during the drilling high viscosity is required for carrying drilling cuttings to the surface, however during cementing main purpose is to make hole ready for the cementing and degrade gel on the wall of the open hole. That’s why using turbulent flow hole is cleaned from the mud gels.
- End of the cementing was determined by using mud front position, where it has been shown hydraulic overlap is guaranteed also after cement is pumped into the hole, it is displaced to the annulus by using drilling mud and that’s why mud pumped after tail cement.

- During the cementing of the 34/10-1 well 340 mm section cement weight with lower density but higher compressive strength is used, where this cement is generally used in ERD (extended reach drilling) wells or wells with smaller mud window. So, implementation of this cement has another advantage [17]. However, it is also important to state that second stage cementing tools can be considered for avoiding big ECD happening in the well [3].
- Final key thing that was question is that why always higher circulation rates, higher running speeds was used. Although limits of ECD created in the well was analysed during the simulations, doing operations fast has advantages. Thus, during the drilling and well operations, time means money, hence rig rented by operating company has daily rig cost, which is several hundred thousand dollars per day. So, the company pays for extra money for the extended duration of the operations. That's why, apart from operational limits, running speeds, circulation rates and cement displacement rates were taken as high as possible in order to shorten operation time.

4.3 Chapter Summary

In the chapter, results from simulations, a possible cause of high ECD, its mitigation methods, operational margins, and industry desired parameters are presented. It is important to summarize that changing wellbore design and its structure is hydraulically possible.

CONCLUSIONS and RECOMMENDATIONS

Conclusions

In this thesis, main objectives was optimize equivalent circulating density in the wellbore conditions and in order to fulfil this objective on the actual well models were created in the Drillbench Software. It is possible to say that all of the objectives of the thesis were delivered. Based on the results obtained from software approach, following conclusions are made.

- By using data of the pore pressure fracture gradient of the 34/10-1 and 34/10-3 wells, drilling mud program as well as rheology designed for the wells. Also, in the expert input of the section of the software, gel model was entered where it was possible to see real drilling fluid model. Furthermore, in both of the wells casing sections cementing sequence was programmed according which simulations were carried out.
- ECD management was carried, while running casing, mud conditioning and cementing casing in place. Thus, by controlling casing running speed because of the surge, fracturing of the open hole is prevented. In particular, 340 mm casing section in 34/10-1 well, acceleration and minimum string running speed were optimized and as a result high ECD is completely mitigated. Also during mud conditioning and cementing by using lower flow rates neither fracture gradient exceeded nor any wellbore issues are encountered.
- During the software approach, rheology of the mud, its properties were analysed. Thus, different mud weights and rheology were used for surge analysis and cementing operations. Effect of the gelling on the ECD was examined and best approach was established.

After comprehensive and wide studies, analysis, case studies and research the following recommendations are gained.

Recommendations

Software analysis on the well models shows that changing design of the both of the wells is feasible in the case of safe execution. Below summary of main recommendations are presented.

- ECD can be optimized by using low running speeds, low flow rates of the fluids. Also, second stage cementing tools can be used for avoiding possible hole instability issues.

- For the cementing of the casings, apart from different type of cements, for achieving good cementing in the annulus and casing, 10% hierarchy in the density rule has to be obeyed.

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