Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Geoscience and Petroleum

Kristina Marcelie Holen Talleraas

Surge and Swab Simulations

A Sensitivity Study on Surge and Swab Pressures Using WellPlan Simulations

Master's thesis in Petroleum Geosciences and Engineering
Supervisor: John-Morten Godhavn
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Sammendrag

Det er nye tider i energisektoren og det er stort fokus på optimal olje- og gassutvinning. Samtidig som verden ønsker å bevege seg i en miljøvennligretning mot mindre utslipp, er vi i stor grad fremdeles avhengige av olje og gass. Større krav stilles til petroleumsbransjen, og nye løsninger på komplekse problemer må utforskes. Det sies at de «enkle» brønnene allerede er boret, og vi sitter igjen med vanskelige og kompliserte felt. Et viktig problem i boreprosessen som ønskes løst, er å kutte ned på «ikke-produktiv» tid. Dette oppstår når borestrengen må dras ut av brønnen, for eksempel for å skrifte en slitt borekrone, eller ved andre defekter.

Når borestrengen dras ut av hullet, vil trykket i brønnen synke, noe som kan få fatale følger. Fluider kan strømme inn i brønnen grunnet det lave brønntrykket og potensielt forårsake et kick. Dersom dette kicket ikke oppdages, vil det kunne lede til en såkalt blow out, og potensielt ødelegge både rigg og reservoar. Denne trykkreduksjonen som oppstår som følge av å trekke ut borestrengen kalles swabbing. Hastigheten som borestrengen dras ut med har stor betydning for hvor stor denne swab-effekten blir. Det motsatte skjer når borestrengen føres ned i hullet igjen. En trykkøkning vil da oppstå, som også kan lede til andre store skader. Denne trykkøkningen kalles surge-effekt, og dersom trykket blir for høyt, kan dette lede til frakturer i formasjonen som det bores i. Boreslam vil da kunne flyte ut i formasjonen, og potensielt ødelegge reservoaret. Begge scenarioene er verdt å investere tid og penger på å unngå, samtidig som det er ønskelig å la prosessen gå så fort som mulig.

Å estimere trykkfallet og trykkøkningen så nøyaktig som mulig er derfor en svært viktig del av operasjonen. Flere matematiske modeller er utviklet for dette formålet, men fremdeles er det mye usikkerhet knyttet til estimatene. Dette gjelder særlig for kompliserte brønner, slik som de som ligger under dype vann eller er boret horisontalt.

Halliburton har utviklet et boresimuleringsprogram som heter Landmark WellPlan. Dette er mye brukt i industrien idag, og er et avansert program som tar for seg alle spekter av boreprosessen. I denne oppgaven vil to ulike brønner simuleres i WellPlan. Den ene er en relativt enkel brønn med et stort trykkvindu. Den andre er en mer komplisert brønn, med en lang horisontal seksjon, og et lite trykkvindu.

Intensjonen med denne oppgaven er å analysere hvilke parametere som påvirker surge og swab, og i hvor stor grad. Parametere som boreslammets tetthet og viskositet, samt dimensjoner på borekrone, borestreng, BHA og selve brønnen, vil i likhet med hastigheten, i ulik grad påvirke trykkendringene. Også ulikhetene mellom de to brønnene vil bli undersøkt.

Abstract

Surge and swab pressures have for a long time been a problem in the petroleum industry. These pressure changes are mainly related to tripping operations, where the drill string has to be pulled out of the well, normally due to a worn out drill bit, or a broken tool. The desire is to optimize the process and time used to trip in and out of the well, to save time and money, and at the same time not taking any risks. If the tripping speed exceeds a certain limit, the pressure changes in the well may become so severe that the consequences are fatal.

The main focus in this thesis is to identify the parameters affecting surge and swab pressures, and investigate their grade of impact. Halliburton Landmark's WellPlan software will be used to simulate two different well cases and to estimate the equivalent circulating density (hereinafter referred to as "ECD") of the drilling mud downhole. The tripping operation will be simulated at different tripping speeds, altering parameters to observe the change in ECD, which is directly related to down hole pressures. When the pressure increases from surge effects, the ECD will also increase due to compression. For swab pressures, the opposite will happen and the ECD will decrease.

Wellplan calculates ECD by using any desired fluid behaviour model. The Bingham plastic model, the Power Law model and the Herschel-Bulkley model are all tested and used to obtain the best results possible. Both fluid properties, such as density and plastic viscosity, and the geometry downhole, such as the diameter of the bit, drill pipe and open hole, and bottom hole assembly (BHA) dimensions, will affect the ECD. By tripping in and out with different velocities in WellPlan, it is possible to observe which parameters have the larger impact on ECD, hence the surge and swab pressures.

Fluid properties, such as the mud density, plastic viscosity and yield point, were also analysed and shown to have some impact on surge and swab. The impact of downhole geometry is greater, but due to its complexity, it is difficult to predict the different components impact mathematically. It is important to understand the uncertainties of estimating ECD in WellPlan, which factors that are included in the estimation and those who are not. This is in particular important for the drill bit and the BHA, which causes the majority of the pressure changes in tripping operations.

For future work, the mud temperature could be considered in the sensitivity analysis. Also the impact of the BHA to surge and swab could be investigated further with more realistic design and accurate data.

Acknowledgements

This master thesis is the final work of my studies of Petroleum Engineering, with specialisation in drilling technology, at the Norwegian University of Science and Technology.

Woking on this thesis has been challenging, but most of all interesting and very educational. Primarily I want to thank my supervisor, adjunct professor John-Morten Godhavn, for making it possible for me to investigate this exiting topic, and for extraordinary guidance and follow-up on my work. I also want to thank Bjørn Brechan at NTNU and Mohamed Zidan at Equinor for teaching and helping me with the WellPlan simulation program.

Lastly, I want to thank my family for all support through my studies, and all my fellow students at NTNU for making my time as a student in Trondheim fantastic in every way.

Kristina Marcelie Holen Talleraas
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1. Introduction

The petroleum industry meets higher expectations for every day, supplying the world’s increasing need for energy, and at the same time trying to do so in an environmentally and economically responsible way. The wells that are being drilled gets more and more complicated, making the petroleum companies continuously facing new challenges. When accessing complicated formations, with narrow windows between the pore pressure and the fracture pressure, instabilities in the wellbore, and other time-consuming and costly problems, the so called non-productive time at the rig is a huge inconvenience.

A lot of the non-productive time in drilling operations occurs when there is a need to trip out of the well. Problems due to so-called tripping have for a long time been an issue for the drillers. It is desired to go as fast as possible, but to simply pull out the drill string in a fast manner can lead to severe damage of the well. The wellbore pressure decreases, due to what is called swabbing. The opposite happens when the drill string is running into the already drilled well, the pressure increases in the wellbore, which is called surge pressure.

In complex wells, drilled with inclinations or in horizontal direction, or in deep water formations, the well may not withstand major pressure changes because of the narrow fracture/pore pressure window. To estimate the change in pressure as accurate as possible has become more important than ever. This can namely help to reduce non-productive time at the rig, save money, and increase the safety, and reduce environmental damage.

The benefits of increasing the tripping speed is of such enormous value for the drilling companies, that several mathematical models have been developed over the years, with the intention to estimate the pressure changes in the wellbore due to surge and swab. Halliburton Landmark has developed a simulation program called WellPlan, which is the most comprehensive well simulation tool in the industry today.

The objective of this thesis is to study the sensitivity of different parameters effect on surge and swab. Two different cases of real drilled wells are provided and simulated in WellPlan, to do a sensitivity analysis on which parameters affecting surge and swab the most. The fluid flow behaviour models most commonly used today for non-Newtonian fluids, the Bingham Plastic model, the Power-Law model, and the Herschel-Bulkley model will be tested, as well as the parameters that define them. It is also a known fact that the downhole conditions and dimensions of the well is of great significance, and by simulating tripping operations in WellPlan, several parameters of the planned well can be altered to estimate their sensitivity in respect to surge and swab pressures.

2. Fundamentals of Surge and Swab

2.1 Published knowledge

Problems involving surge and swab pressures are well known in the petroleum industry. Already in the early 1900's, it was detected that swabbing could be a reason for fluid influx to the wellbore. Surge and swab effects from tripping the drill pipe can alter the pressure at the bottom of the well with a significant amount. There have been developed many methods to predict the surge and swab effects through the years, each one with different assumptions and conditions.

A semi empirical model to estimate surge and swab pressures for Bingham Plastic fluids was developed by Burkhardt (1961). His model compares actual test results of surge pressure with a mathematical prediction, assuming ideal Bingham plastic fluids, uniform wellbore and fluid flowing at steady state. Schuh (1964) had a similar approach, when developing a power-law fluid model, also assuming steady state flow, in a concentric annulus. Fontenote and Clark (1974) presented a model to determine surge and swab pressure for both Bingham Plastic and Power Law fluids. Mitchell (1988) came up with a dynamic model, including several new factors, such as mud rheology, the elasticity of the pipe and the cement, formation, changing temperatures, and viscous forces. A new dynamic model was then again developed by Crespo et. al. (2010), also accounting for compressibility of the fluid and formation. Two years later, a laboratory experiment was conducted by Srivastav et. al. (2012) confirming that the speed of the trip, mud properties, annular clearance and the eccentricity of the pipe affects the surge and swab pressures highly. Gjerstad et. al. (2013) developed a model to predict surge and swab pressures in real time for Herschel-Bulkley fluids based on differential pressure equations.

2.2 Tripping

During a drilling operation, it is sometimes required to pull the drill string out of the well. Reasons for this may be:

- Need to change a worn out bit
- Change bit size
- Fix damaged drill pipe
- Fix broken tools
- Retrieve loose items in the well

This physical movement of the drill string in or out of the well is called tripping. It is a time consuming process that the drillers want to minimize due to higher costs and non-productive time. Thus, severe problems may occur if the tripping speed is too high. When tripping out, the upward movement of the drill pipe causes friction between the pipe and the drilling mud. The pressure decreases in the well due to the surge effect. The opposite happens when the pipe is tripping in, when the downward movement causes a pressure increase. This is the swab effect.

When tripping, a margin is calculated as an addition to the drilling mud density. This additional density is to provide overbalance to avoid fluid to enter the wellbore. The tripping margin can easily be calculated, according to Skalle [14].

$$trip\ margin\ [sg] = \frac{0.01 * YP}{g(D_{hole} - D_{pipe})} \tag{1}$$

Where
YP is the drilling fluid yield point,
D_{hole} is the diameter of the bore hole,
D_{pipe} is the drilling pipe diameter,
g is the gravitational constant 9.81 m/s^2.

The trip margin is normally around 0.02-0.05 sg, or 20-50 kg/m^3.

2.3 Bottom Hole Assembly

The bottom hole assembly (hereinafter referred to as BHA) is the part at the end of the drill string. At the bottom of the BHA is the drill bit. It may also consist of a drill collar, stabilizer, reamer, heavy weight drill pipe, jarring device, mud motor, directional drilling equipment, MWD, and logging tools. The BHA components functions is to penetrate the formation, stabilization of the drilling, enhancement of the directional control, and the maximization of the drilling performance per se. The various parts of the BHA are explained below.

It is proven that most of the pressure loss in the well happens around the BHA, especially where the annular space is small.

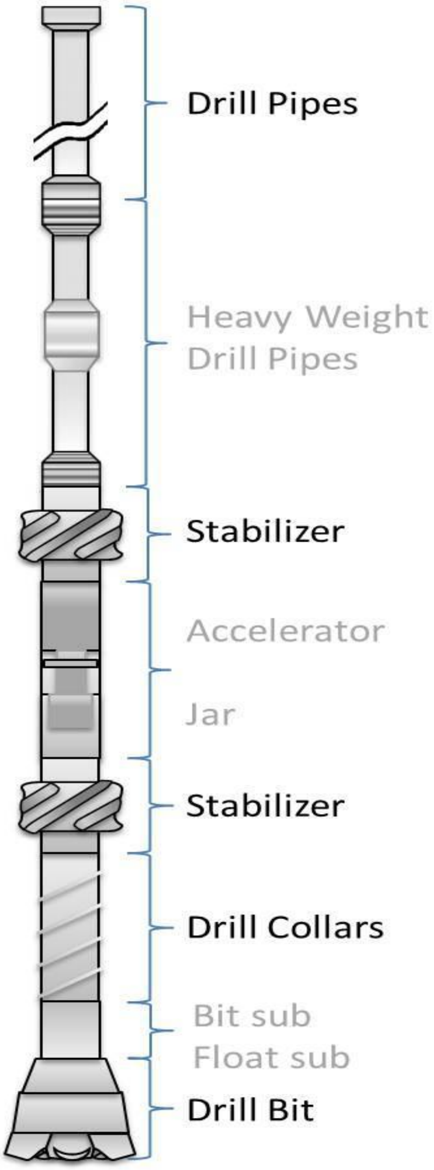


Figure 1: Bottom Hole Assembly Illustration

Heavy Weight Drill Pipe

Heavy weight drill pipes have thicker walls than an ordinary drill pipe, making it much heavier. Their main functions is to provide a flexible transition to the drill pipe, and add weight to the bit.

Drill Collar

In similarity to the heavy weight drill pipe, the drill collar is a component to add weight on the bit, hence usually made of carbon steel. Some drill collars have a spiral shape on the outside to avoid full contact to the wellbore wall, and to allow for more room for the fluid to flow.

MWD

Measurement while drilling is a drilling logging tool, providing real time data, like wellbore position, directional data and information of the drill bit.

Stabilizers

Stabilizers are used in the BHA due to the purpose of avoiding sidetracking and vibrations when drilling the well. There may be several stabilizers in the BHA, one right above the bit, and one between heavy weights or drill collars. They consist of a hollow cylindrical body and blades for stabilization. Typically these are made of hard material like high-strength steel.

Drill Bit

The drill bit is the lowest part of the BHA, and is designed to cut the formation by rotating cones consisting of very hard material. The bit also has several nozzles, where the drilling fluid comes out through the drill string and into the well. The dimensions of the drill bit is difficult to consider in calculations, due to the geometry complexity.

2.4 Drilling fluid

The mud system has several important functions in a drilling operation. It is pumped from the mud pit through the drill string, going out through the bit nozzles, and carry cuttings from the well back up to the surface through the annular space. From here it goes to a shaker where the cuttings are filtrated out, and the mud returns to the mud pit. Thus, the removal of cuttings and hole cleaning is not the only function of the mud. The main functions of the mud is as follows:

- Cleaning, carrying out cuttings
- Controlling formation pressure
- Maintaining stability in the wellbore
- Sealing permeable formations
- Avoiding formation damage
- Cooling and supporting the drill bit and string
- Controls corrosion
- Helps to obtain information by logging
- Minimizing the impact on the environment

2.4.1 Types of drilling fluid

Every well that is drilled is unique, and thus requires a customized mud program to go with the different conditions. Several advanced and complex fluid formulations have been made, but they can be classified in three general groups:

- **Water-based mud** (WBM) has water as the liquid component, often mixed with chemicals, solids like clay and cuttings, or salt. This is the most commonly used mud, due to its simplicity and availability. It is also the most economically responsible.

- **Oil-based mud** (OBM) is mud where oil is the main liquid component, like diesel or a mineral oil. It also contain water, with an oil/water ratio normally between 70/30 and 90/10. Bentonite is commonly used to control viscosity, barite to increase the density, and lime to maintain a high pH-value. OBM's are more expensive than WBM's, and requires more consideration regarding to discharge and recycling. However, the OBM provides better wellbore stability, lubricity, and is more resistant to heat.

- **Synthetic-based mud** is based on synthetic oil. It has the properties of an OBM, but with less toxicity. It requires the same considerations as OBM, but is far less used.

2.4.2 Drilling fluid properties

The different properties of drilling fluid play all an important role for a successful drilling operation, and are the easiest changeable variables of the process. Each mud program used to drill a well is designed for the specific individual conditions of the well. The American Petroleum Institute (API) described the drilling fluid measurements that are necessary to describe the main characteristics:

- Density
- Viscosity and Gel Strength
- Filtration
- Concentration of sand
- Methylene Blue Capacity
- pH
- Chemical analysis

The characteristics of importance in this sensitivity study will be describes more in detail below.

Density

The control of density of the drilling fluid is critical to maintain the wellbore pressure within the safe limits. If the density is too high, the formation can fracture. If the density is too low, it may lead to influx of formation fluids. Fluid density is defined as mass per volume, and is directly related to the average specific gravity of the solids in the fluid. It is often referred to as mud weight, expressed in pounds per gallon (lb/gal), pounds per cubic foot (lb/ft3), kilograms per cubic meter (kg/m3) or specific gravity (sg). Using the right fluid density for the individual formation is important. Strong formations can be drilled with low density muds, like 1000 kg/m^3, but for example shale under high pressure can require a mud density over 2000 kg/m^3.

Viscosity

Viscosity is the measurement of a fluid's flow resistance, under deformation by shear stress. The higher the viscosity is, the "thicker" the fluid. A rotating viscometer is used to measure the viscosity of a fluid, by measuring the shear strength required to break the internal tension of the fluid. The viscometer is driven constantly at six standard velocities, 600, 300, 200, 100, 6 and 3 RPM, and the shear stress is measured for each velocity. Viscosity is expressed in centipoise (cp) which equals one millipascal second (mPa s). During drilling operations, the drilling fluid viscosity can be increased by adding polymers or clay, or decreased by adding water or chemical thinners.

The Bingham plastic viscosity can be calculated from the dial read from the viscometer at 600 and 300 RPM;

$$PV = \theta_{600} - \theta_{300} \qquad (2)$$

Yield Point

Yield point is the stress required to initiate flow of the fluid. The yield point can easily be obtained from the recorded values of shear stress from the rotating viscometer, and is expressed in pounds per square feet (lbs/ft2). It is a measurement of the electrical forces in the fluid when it flows.

According to Bingham, the yield point can be calculated from the dial read from the viscometer;

$$YP = \theta_{300} - PV \tag{3}$$

θ_{300} = Dial reading when the viscometer is running at 300 RPM
PV = Plastic Viscosity

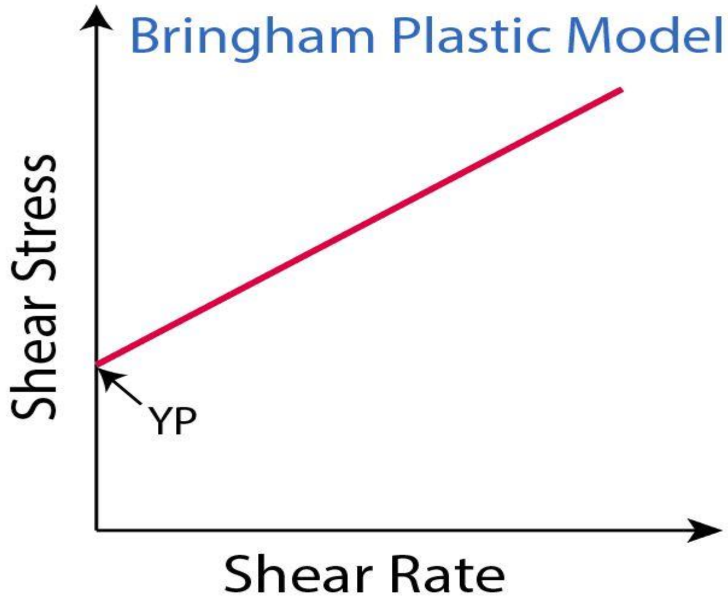


Figure 2: Relationship between shear rate, shear stress and yield point

Rheology

The definition of rheology is the physics of the flow and deformation of the matter, and is together with annular hydraulics very important for the wellbore stability and the hole cleaning. Rheology and hydraulics are based on mathematical models.

We separate between Newtonian and non-Newtonian fluids. Newtonian fluids are characterized by one single value for viscosity, changing with temperature but not with the relationship between shear stress and shear rate. The viscosity of a Newtonian fluid is defined by

$$\mu = \frac{\tau}{\gamma} \tag{4}$$

Where μ = viscosity, τ = shear stress and γ = shear rate.

Most drilling fluids are non-Newtonian fluids. The relationship between shear stress and shear rate is called the effective viscosity, and is not constant. The shear rate in non-Newtonian fluid is expressed as the change of velocity in the flow path between fluid layers

$$\gamma = -\frac{dv}{dr} \tag{5}$$

Due to the complexity of non-Newtonian fluids, there has been developed several rheological models, where the Newtonian is the simplest.

2.4.3 Flow conditions

Fluid flow is either in a laminar, transition, or turbulent state, depending on a value called Reynolds number (a dimensionless value) that can be calculated from

$$Re = \frac{\rho\, v\, D}{\mu} \tag{6}$$

Where
ρ = fluid density,
v = velocity,
D = pipe diameter and
μ = dynamic viscosity.

The flow is then defined as

- Laminar for Re < 2300
- Transient for 2300 < Re < 4000
- Turbulent for Re > 4000

Laminar flow is often found in low velocity regimes. The fluid flows in smooth layers, and the particles motion is orderly, moving parallel to the pipe wall along straight lines.

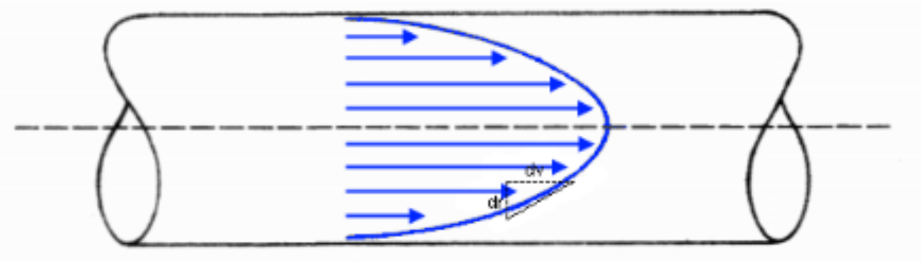


Figure 3: Laminar flow

The transition zone is the state where the fluid is in transition from laminar to turbulent flow. Both laminar and turbulent flow patterns can be found.

Turbulent flow occurs at higher velocities, and larger pipes. The flow pattern is out of order, in random and chaotic motions. A slim layer of order can only be found near the wall.

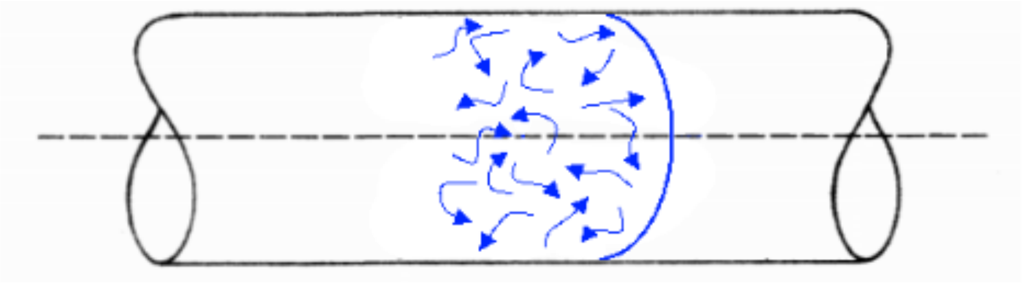


Figure 4: Turbulent flow

When the flow changes from laminar to turbulent, the pressure increases drastically.

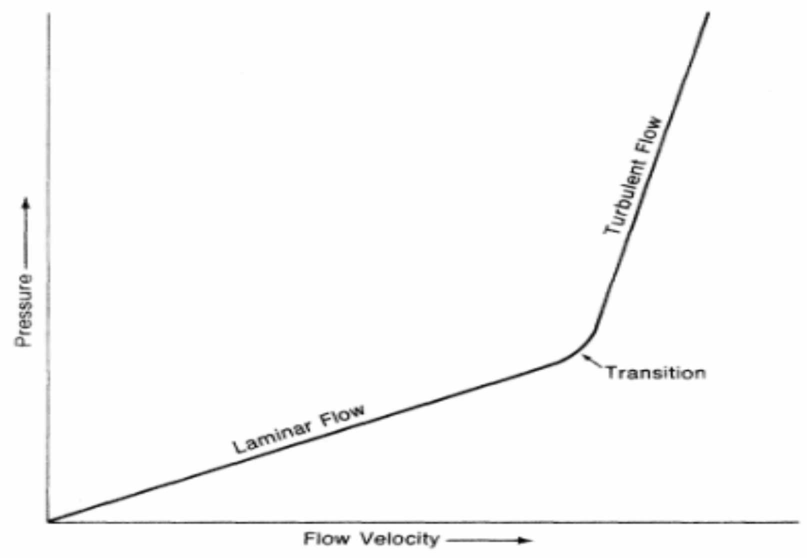


Figure 5: Development from laminar to turbulent flow

2.4.4 Frictional pressure

When drilling fluid is circulating in the well, there will always be a certain pressure loss due to frictional forces between the fluids, the wellbore wall, and the drill pipe. The frictional pressure loss is a function of the flow rate, the geometry of wellbore/drill pipe, the fluid rheology and properties, and the flow regime.

When the Reynolds number is known, the friction factor f can be calculated;

$$\mathrm{f} = \frac{0.0791}{{N_{Re}}^{0.25}} \tag{7}$$

for laminar flow conditions, and

$$\mathrm{f} = \frac{16}{N_{Re}} \tag{8}$$

where $N_{Re} < 2{,}100$ for transient and turbulent flow conditions.
Hence, the total frictional pressure loss in the annulus can be calculated from

$$\frac{dp_f}{dL} = \frac{f\,\rho\,{v_{avg}}^2}{21.1\,(D_2 - D_1)} \tag{9}$$

Where f = friction factor, ρ = fluid density, v_{avg} = average fluid velocity, D_2 = inner diameter of wellbore wall, and D_1 = outer diameter of drill pipe

2.4.5 Fluid velocity

In order to calculate the frictional pressure loss, an estimation of the average fluid flow velocity is required. Velocity is the relation between flow rate and cross sectional are of the conduct channel, in this case between the wellbore wall and the drill pipe;

$$v_{avg} = \frac{Q}{A} = \frac{4\,Q}{\pi\,(D_2^2 - D_1^2)} \tag{10}$$

Where
Q = flow rate,
A = flow area,
D_1 = diameter of drill pipe,
D_2 = inner diameter of wellbore wall.

2.4.6 Equivalent Circulating Density

Equivalent circulating density, ECD, is defined as the apparent density of the drilling fluid when adding friction from the annulus to the actual fluid density. This is of great importance when the window between pore pressure and fracture pressure is narrow. The pressure and temperature conditions down hole will affect the mud density and must be taken into account. High temperatures will decrease the density and it will increase with low temperatures. If the pressure increases, the fluid will be compressed, the volume will decrease, and the density will increase.

ECD is a function of pressure losses;

$$ECD = \rho_{mud} + \frac{\Delta P_{annual\,friction} + \Delta P_{cuttings} + \Delta P_{surge\,\&\,swab} + \Delta P_{rotation} + \Delta P_{acceleration}}{g\,z} \tag{11}$$

Where g = 9.81 m/s^2
and z is the length of the section in meters.

Surge and swab, and annular friction pressure loss will only be considered, since the others are fairly small compared. The ECD formula can be reduced to

$$ECD\ [ppg] = \rho_{mud} + \frac{\Delta P_{annular\,friction}}{0.052 * TVD} \tag{12}$$

Estimating ECD is an important function of surge and swab predictions. The ECD will directly be affected by the pressure change, and will read a lower value than the actual density when swabbing occurs, and a higher value for surge.

2.4.7 Clinging Constant

The Cling constant, K, represents the mud clinging to the wellbore wall, creating a “new” diameter. Burkhardt obtained the correlation for K_C by using complex equations derived from the Bingham Plastic Model. Surge and swab pressures will be most significant for small annular clearances, where the value of K_C approached 0.5. It may be expressed as

$$K_C = \frac{a^2 - 2a^2 \ln a - 1}{2(1-a^2)\ln a} \tag{13}$$

for a laminar flow, where a is the ratio of pipe diameter to hole diameter. For a turbulent flow, the Clinging constant may be expressed as

$$K_C = \frac{\left(\sqrt{\frac{a^4 + a.}{1+a}} - a^2\right)}{1-a^2} \tag{14}$$

The Clinging constant is rarely mentioned in literature, and is very often neglected in calculations.

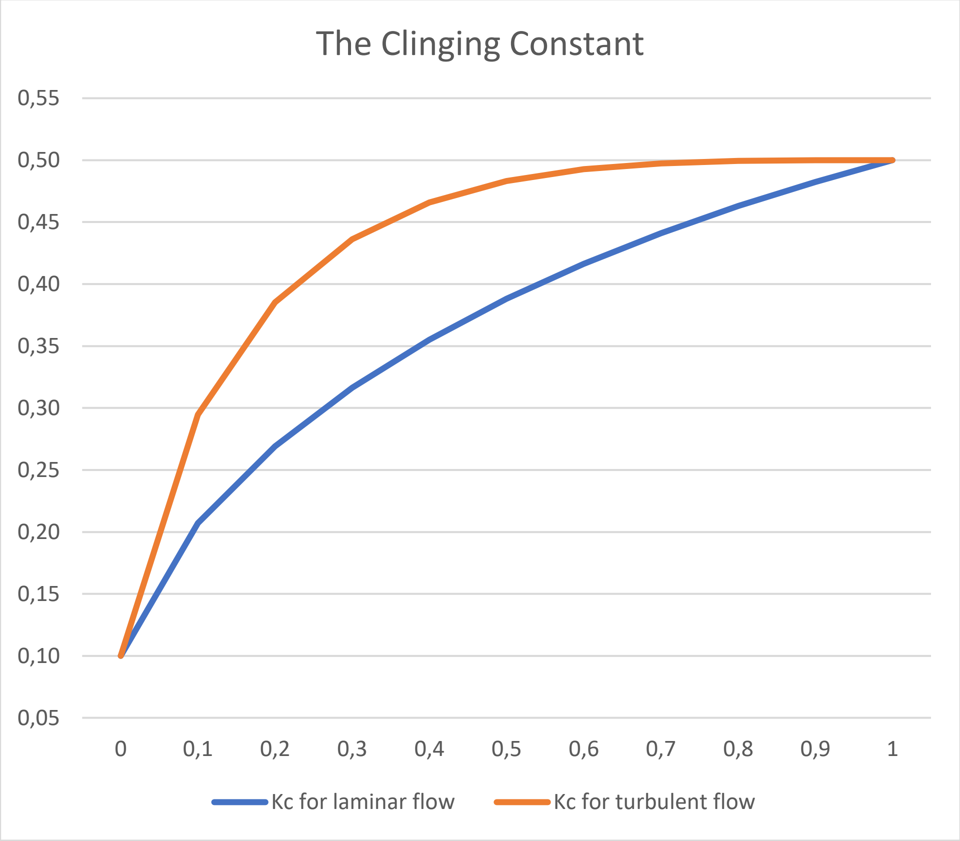


Figure 6: Clinging illustration

2.5 Challenges related to surge and swab

Losses of drilling fluid

One major issue with surge pressure is loss of drilling fluid. If the margin between pore pressure and formation pressure is slim, the surge pressure may cause the formation to crack open and the drilling fluid may enter the formation. If the loss is small, it can be controlled by increasing the viscosity of the drilling fluid by adding for example bentonite or polymers. If severe or total loss occur, it may be difficult to regain the circulation with increased viscosity. In these cases, it may be necessary to cement the location where the formation fractured, and then continue the operation. This is both expensive and time consuming, so to avoid this is highly valued.

Fluid influx

If the formation pressure surpasses the pressure from the drilling fluid in the wellbore, the formation fluids will enter the wellbore. This may be the consequence of swabbing, causing the pressure to drop when tripping out of the well. Fluid influx may develop into a kick, or even worse, a blowout – both results described below:

Kick

A kick is the result of a fluid influx. Formation fluid enters the wellbore, and kick the drilling fluid out of the well, causing a mud pit volume increase. There are two different categories of kicks, underbalanced and induced.

Underbalanced kick is when the mud weight is too low to keep the formation fluid at its place. This is usually not a problem in tripping operations, unless gas enters the well and the mud weight is not sufficient. Induced kick happens when dynamic or transient pressure effects decreases the wellbore pressure, such as swab pressure.

Controlling the fluid influx, hence detecting kicks, is important considering the severe consequences. If a kick is detected at the surface, the drillers need to take proper action, and kill the well. This is normally done either by pumping out the kick fluid before pumping down mud with increased density called kill mud, or by pumping out the kick fluid in one circulation using the kill mud.

Blow out

If the proper actions are not taken when a kick occurs, it may lead to a blow out; a completely uncontrolled flow of reservoir fluids in the wellbore. There are three main types of blow outs; surface, subsea and underground. Surface blow outs are the most common, and the force of the fluid flowing all the way to the surface may be strong enough to destroy the rig, and surrounding area. A subsea blow out is the hardest to deal with due to the severe effect on the environment, when the formation fluid mixes with water. Underground blow outs are rare, and happens when fluid from high pressure zones flows uncontrolled to zones with lower pressure. It may take a long time to obtain control after a blow out, and the risk of human lifes, the environmental and material damages, and the economical losses makes it a huge priority to avoid any type of blow out.

Eccentric annulus

The models developed to predict surge and swab, assumes the well to be concentric. For inclined and horizontal wells, this assumption may not be valid. The drill pipe tends to lay down on the low side of the well, making more room over the pipe for the fluid to flow. The surge and swab pressure of eccentric wells can be reduced significantly. There are not many studies on surge and swab on eccentric wells, and it is difficult to model mathematically.

3. Mathematical Fluid Models

There have been developed several mathematical models to describe fluid flow behaviour, originated from the relationship between the shear stress and shear rate. A generalized shear stress/shear rate relationship for non-Newtonian fluids does not exist, because the relationship depends on the individual fluid composition. The mathematical methods are only a close approximation of the non-Newtonian fluid behaviour. In the petroleum industry, the most common models for non-Newtonian fluids are the Bingham Plastic Model, the Power Law Model, and the Herschel-Bulkley Model.

3.1 Bingham Plastic Model

E.C Bingham discovered in 1916 that some fluids required to be exposed to a force greater than the fluid yield point to initiate the fluid to flow. The relationship between shear stress and shear rate for Bingham Plastic Model is expressed as

$$\tau = \mu_p \gamma + \tau_y \tag{15}$$

where τ = shear stress,
τ_y = yield point,
μ_p = plastic viscosity,
γ = shear rate,
and $\tau > \tau_y$.
The plastic viscosity is the lowest value the effective viscosity may have at an infinite high shear rate.

The Bingham Plastic model is often found insufficient to use in complex drilling fluid calculations, since the drilling fluid behaviour is normally not completely plastic.

3.2 Power Law Model

Drilling fluids most commonly behave somewhere in between Newtonian and Bingham Plastic. This behaviour is referred to as pseudoplastic, and can be mathematically defined by the Power Law Model,

$$\tau = K \gamma^{n} \tag{16}$$

Here, K and n are constant. K is called the consistency factor, and describes the fluid thickness. n is called flow behaviour index, and is a measurement of the degree of non-Newtonian behaviour. For n = 1, the fluid is Newtonian, and for pseudoplastic fluids, n is below zero. If n is greater than 1, the fluid is classified as dilatant.

3.3 Herschel-Bulkley Model

The Herschel-Bulkley Model is often referred to as “Yield Power Law”. It includes the Power Law pseudoplastic behaviour, and the Bingham Plastic yield stress.

$$\tau = \tau_0 + K \gamma^{n} \tag{17}$$

Herschel-Bulkley is a widely used model due to its good approximations for both WBM and OBM.

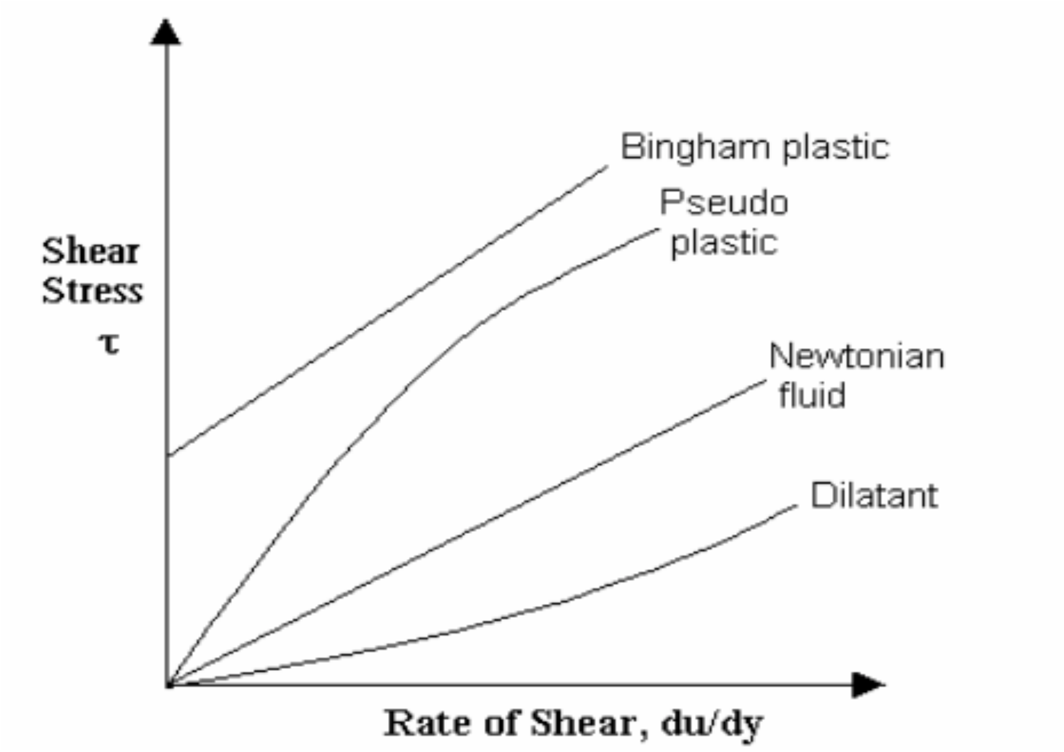


Figure 7: Fluid behaviour relative to shear rate and shear stress

4. Case study

Data from two different wells are obtained, simulated in WellPlan, analysed and compared in this thesis.

4.1 WellPlan

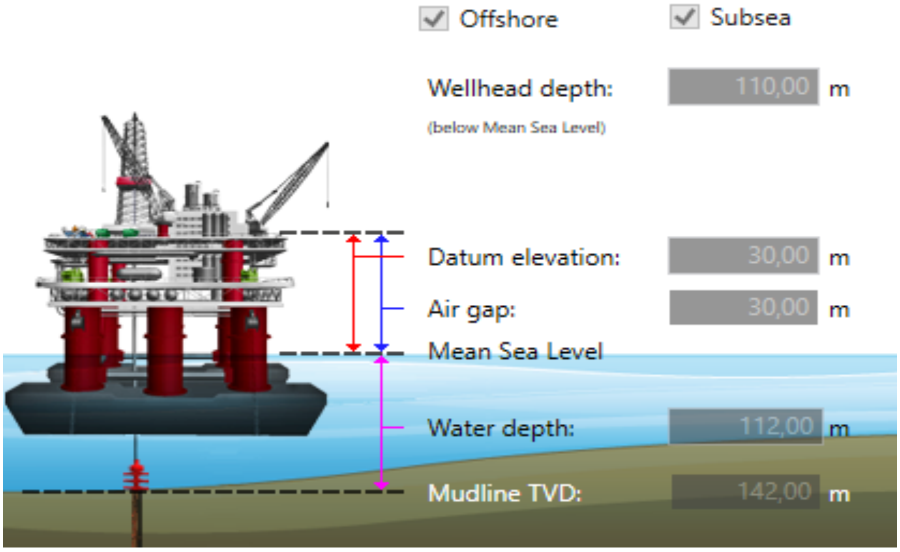
When an operator is planning the drilling of a well, many factors need to be taken into account. Well planning in general is one of the most challenging tasks of drilling engineering, to ensure the well is drilled in a safe and economical matter for best possible production. To obtain a big picture, Wellplan was developed by Halliburton. Wellplan is a drilling simulation program, with 8 modules to simulate and obtain different outputs. The modules are

1. Torque Drag
2. Hydraulics
3. Well Control
4. Surge and Swab
5. OptCem
6. Critical Speed
7. Bottom Hole Assembly
8. Stuck Pipe

In this sensitivity study, only the hydraulics analysis module will be used. The hydraulic analysis module provides outputs that can be used to model pressure losses across the circulating system, estimating the ECD across the annulus. It considers temperature effects, different rheological models, the fluid compressibility, Viscometer readings, critical fluid velocity, and bit size. This is the simplest way to estimate surge and swab pressures in Wellplan, since the surge and swab analysis module requires more inputs and is more difficult to manage.

4.2 Case 1

A subsea well with an air gap of 30 meters and water depth of 112 meters. The well is drilled to measured depth of 3020 m. The TVD is 1985 m. Casing is set at 1722 meters, and a 12 ¼ inch open hole section is drilled down to 3020 meters.



☑ Offshore ☑ Subsea

Wellhead depth: 110,00 m
(below Mean Sea Level)

Datum elevation: 30,00 m

Air gap: 30,00 m

Mean Sea Level

Water depth: 112,00 m

Mudline TVD: 142,00 m

Figure 8: Rig Case 1

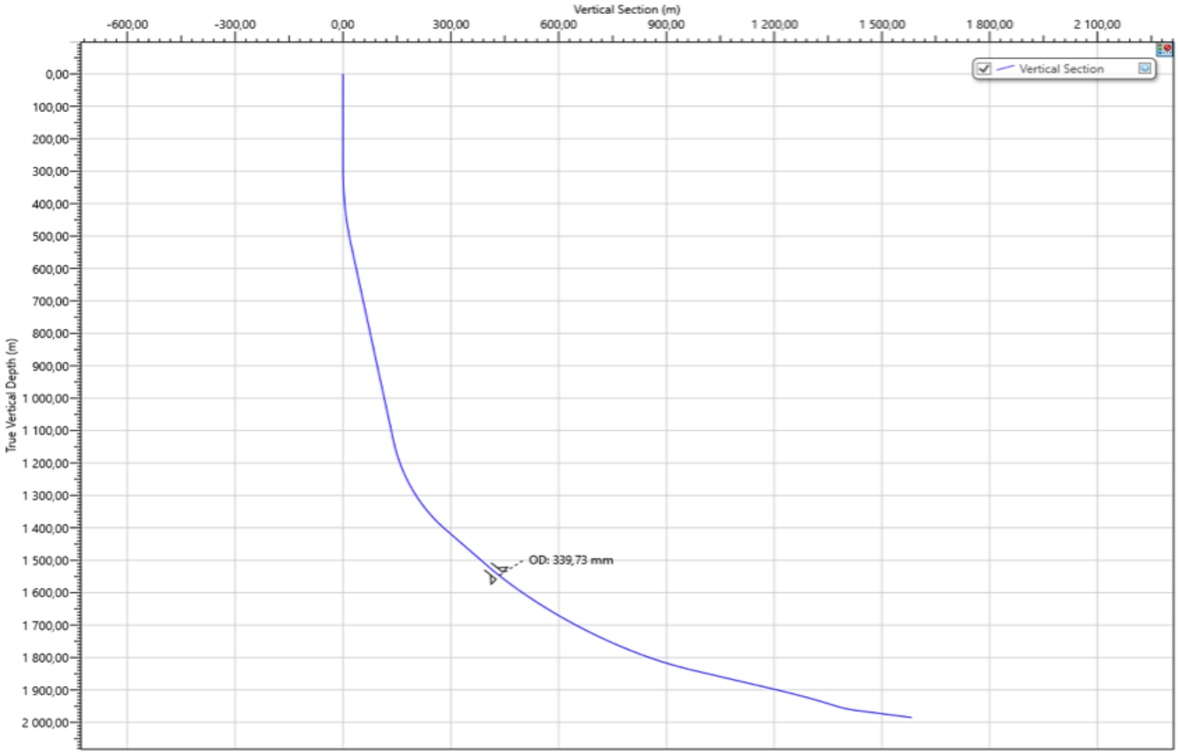


Figure 9: Wellpath Case 1.

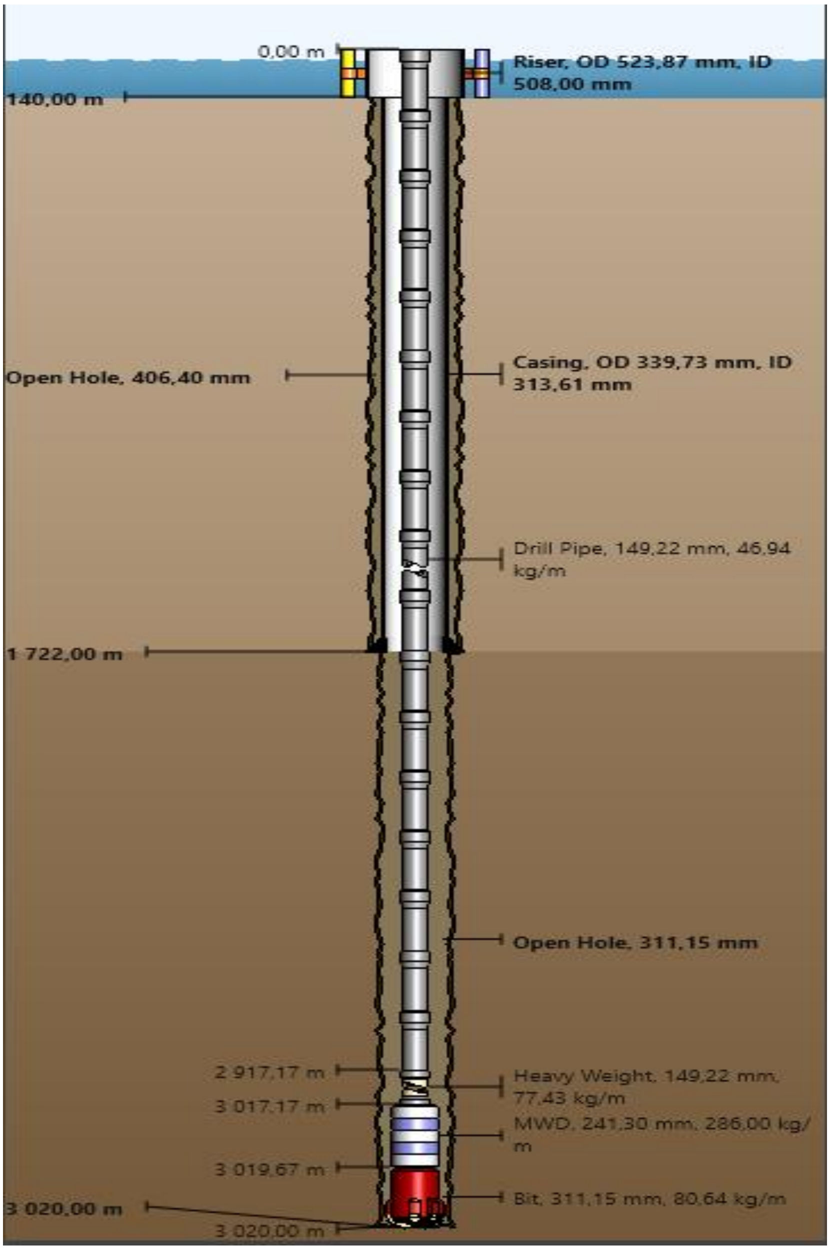


Figure 10: Well Case 1

The well is drilled with a 12 ¼ inch polycrystalline diamond bit, with a length of 0.33 meter, and the bottom hole assembly contains of a MWD-tool above the bit, with a length of 2.5 meter, outer diameter of 9 ½ inch, and a heavy weight drill pipe of 100 meters, with an outer diameter of 5.875 inch, same as the drill pipe.

The drilling mud is an oil based mud, with 80% mud and 20% water. The mud rheology data of the mud is

- Base density 1410 kg/m^3.
- Plastic Viscosity 43.43 cp.
- Flow behaviour index n = 0.79.
- Consistency factor K = 0.1846.
- Yield Point 11.903 lbf/$100ft^2$.

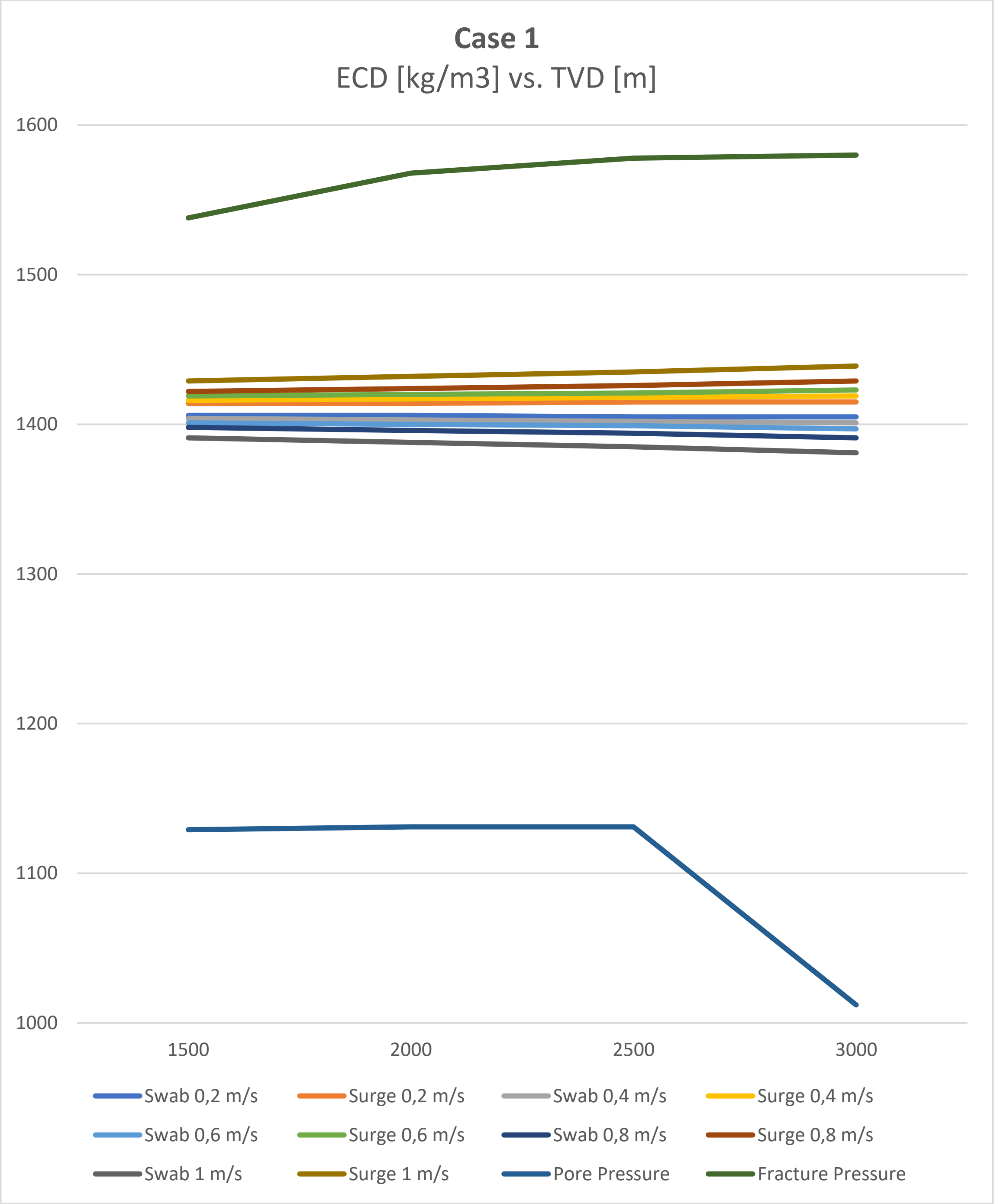


Figure 11: ECD vs. Depth Case 1

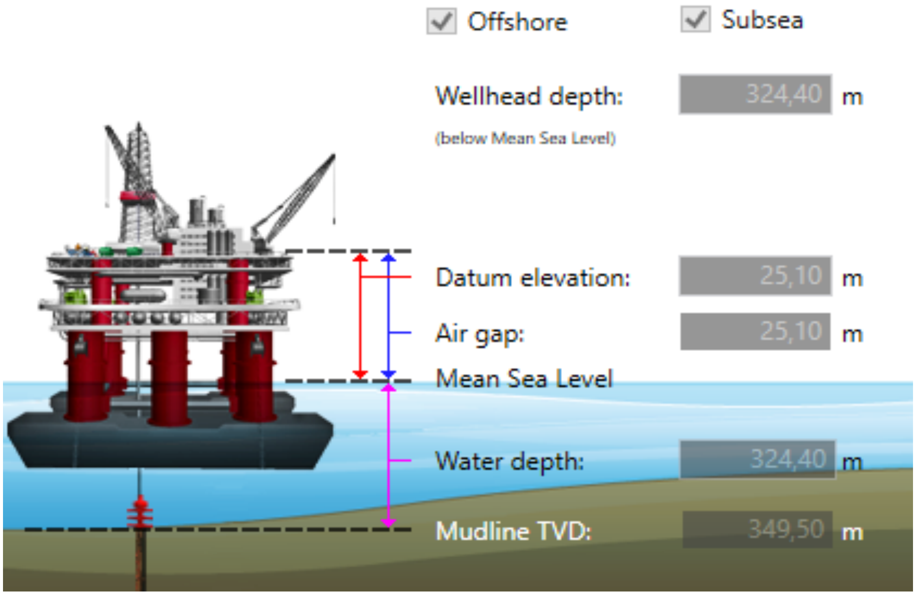
A defining set of pore pressure data and formation fracture data is provided. The drilling mud density needs to be within those limits, and the window in this case is wide, allowing bigger alterations in the parameters affecting the effective circulating density down hole. The surge and swab effects in this case is inversely proportional to each other, so all collected data is for simplicity for the swab effect when tripping out of the well.

Known tripping data for this well:

- ECD = 1389 kg/m^3 for 0.4 m/s tripping out
- ECD = 1385 kg/m^3 for 0.5 m/s tripping out

4.3 Case 2

This is also a subsea well, with an air gap of 25.1 meter, water depth of 324.4 meter. The well is drilled down to TVD 1578 meters, and a 9.66 inch casing is set at 2325 meters measured depth. The total measured depth of the well is 7182 meters, with an approximately 5000 meters long horizontal 8 ½ inch open hole section.



☑ Offshore ☑ Subsea

Wellhead depth: 324,40 m
(below Mean Sea Level)

Datum elevation: 25,10 m

Air gap: 25,10 m

Mean Sea Level

Water depth: 324,40 m

Mudline TVD: 349,50 m

Figure 12: Rig Case 2

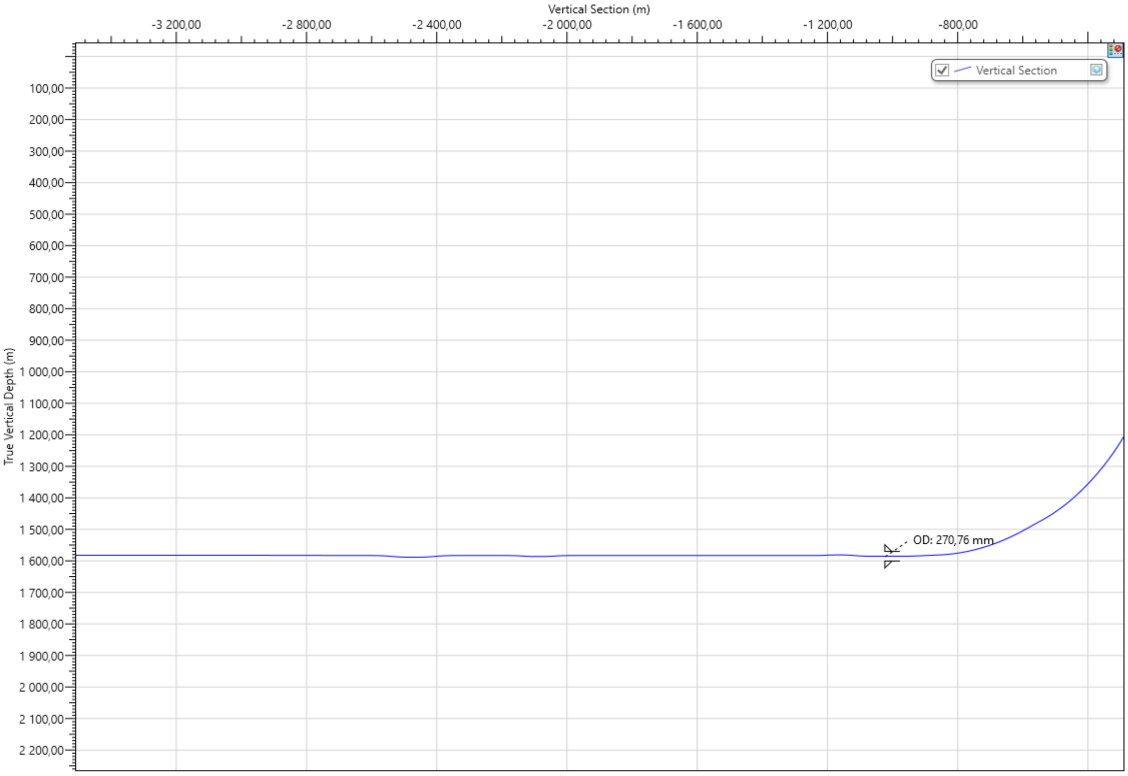


Figure 13: Wellpath Case 2

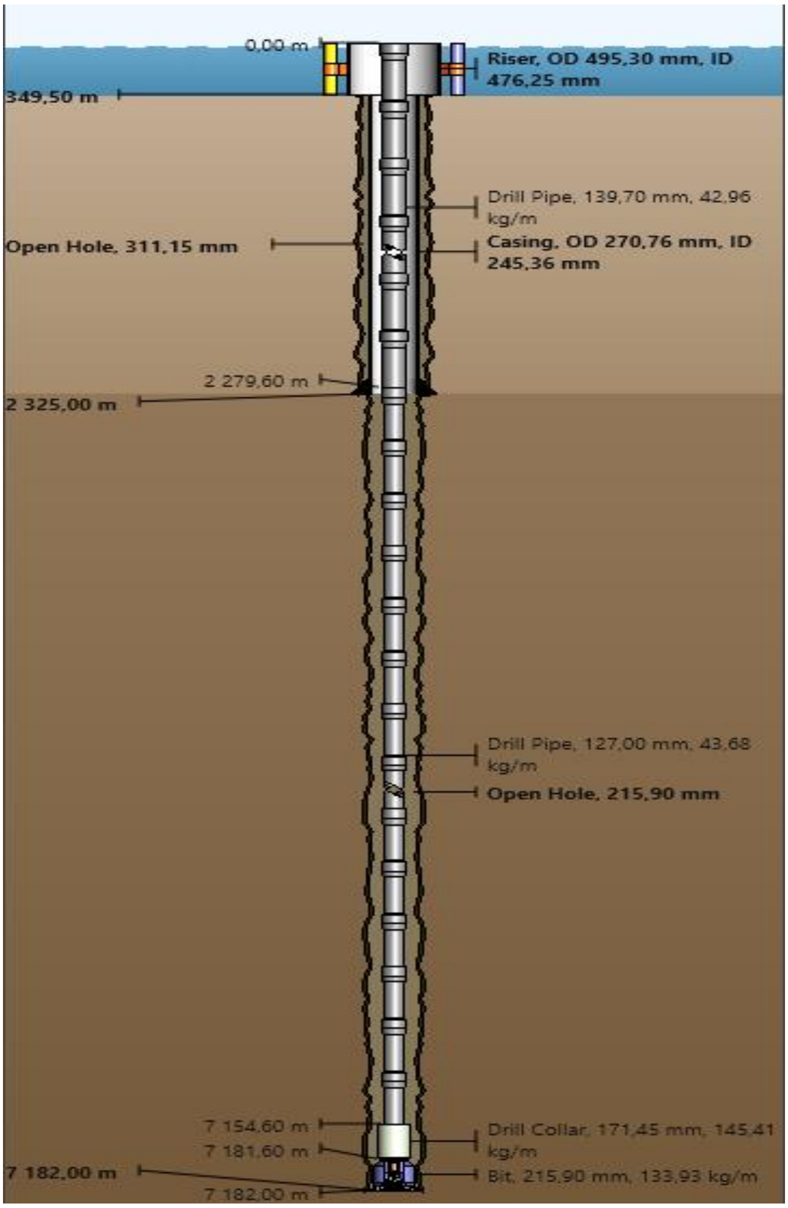


Figure 14: Well Case 2

The well is drilled with a 8 ½ inch bit, with a length of 0.4 meter. Two different drill pipes are used, one 5 ½ inch drill pipe down to 2280 meters, and then a 5 inches drill pipe down to 7155 meters. Above the bit, there is a 27 meters long drill collar with an outer diameter of 6 ¾ inch.

The drilling mud is a 1,25 Aquadrill water based mud. The mud rheology data of the mud is

- Base density 1250 kg/m^3.
- Plastic Viscosity 12.81 cp.
- Flow behaviour index n = 0.48.
- Consistency factor K = 0.9288.
- Yield Point 2.265 lbf/100ft^2.

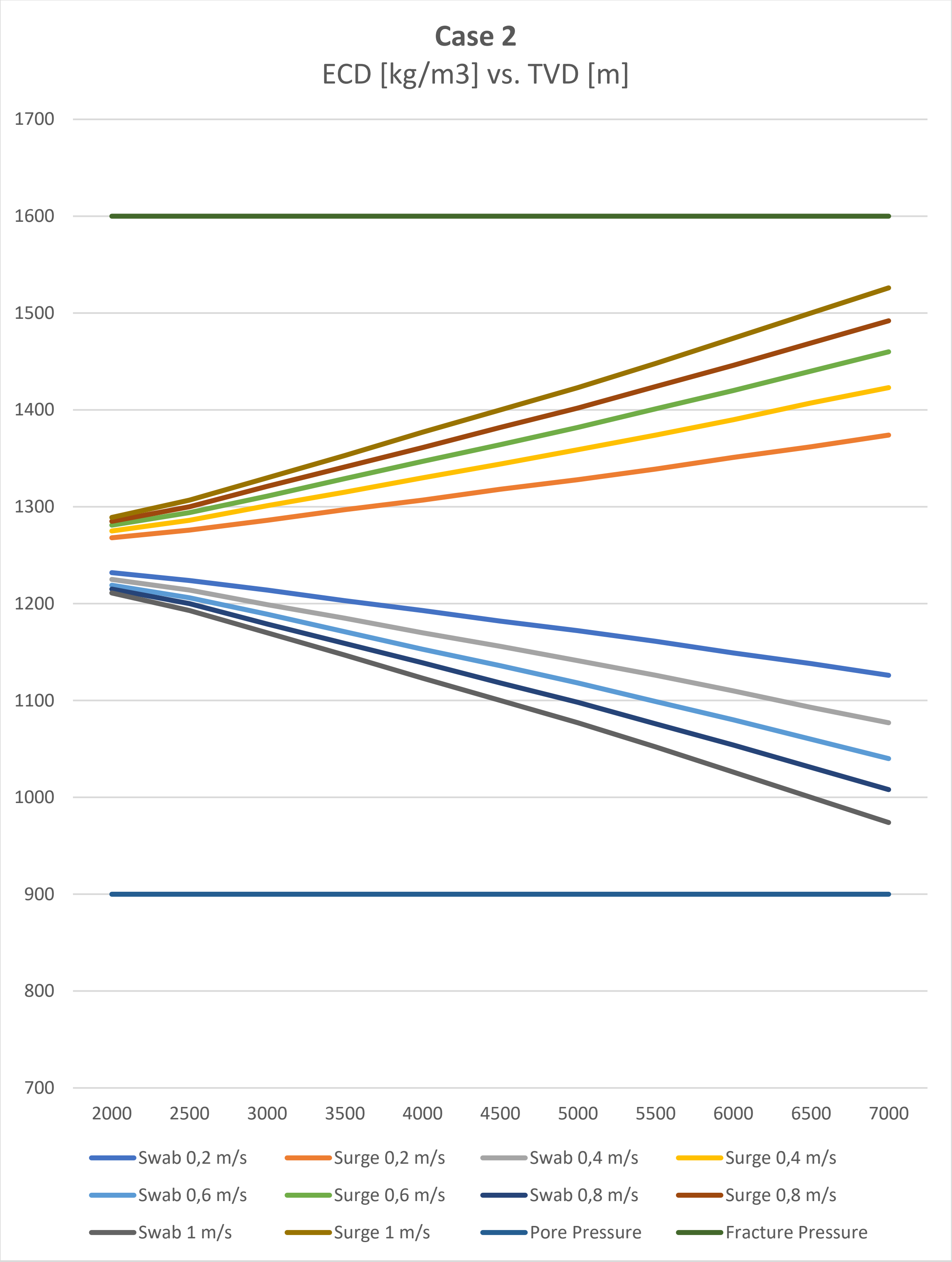


Figure 15: ECD vs. TVD Case 2

The pore and fracture pressure are defined with one single point, respectively 900 and 1600 kg/m^3. Comparing to case 1, it is clear that the swab pressure increases more drastically with high velocity, and the ECD are close to the pressure limits, making case 2 less flexible than case 1.

5. Sensitivity Analysis

The results of the chosen parameters sensitivity to surge and swab pressures will be presented for case 1 and case 2 respectively. The calculated pressure changes in WellPlan will come to sight through changes in the equivalent circulating density. ECD is as mentioned in chapter 2, directly affected by pressure changes in the well. For surge effects, the increase in the well pressure will compress the fluid volume, hence increase the ECD to a higher value than the actual mud density at surface. For swab effects, the ECD is expected to decrease due to the decreasing pressure. The effects of surge and swab pressures on ECD estimated in WellPlan are always inverse proportional to each other, independent of which fluid flow behaviour model used, parameters changed or tripping speed selected. The results will be presented graphically with ECD [kg/m^3] versus tripping speed [m/s], where the cases are tested with 0.2, 0.4, 0.6, 0.8 and 1.0 m/s. In a typical tripping operation, the speed rarely exceeds 0.5 m/s, but the higher velocities are chosen to provide an enhanced sensitivity study of the parameters, and considering the desired goal for the industry is to reduce this non-productive time.

The chosen parameters for this sensitivity analysis are

- Fluid Behaviour Models
  - Bingham Plastic
  - Power Law
  - Herschel-Bulkley
- Mud density
  - Density sensitivity using the Bingham Plastic Model
  - Density sensitivity using the Power-Law Model
  - Density sensitivity using the Herschel-Bulkley Model
- Plastic Viscosity
  - Plastic Viscosity for Bingham Plastic fluids
  - Flow Behaviour Index for Power-Law fluids
  - Flow Behaviour Index for Herschel-Bulkley fluids
  - Consistency Factor for Power-Law fluids
  - Consistency Factor for Herschel-Bulkley fluids
- Yield Point
- Bottom Hole Assembly
  - Length
  - Diameter
- Annular Clearance
  - Scenario 1: drill pipe diameter
  - Scenario 2: open hole and bit diameter
- Bit dimensions

5.1 Case 1 Results

5.1.1 Fluid Flow Behaviour Models

As discussed in chapter 3, several models are developed to estimate fluid flow behaviour. For this sensitivity analysis, both Bingham Plastic, Power-Law and Herschel-Bulkley model are used to evaluate the results. For this case, it is known that tripping out with a speed of 0.4 m/s will decrease the ECD to 1389 kg/m^3, and at 0.5 m/s the ECD reduces further to 1385 kg/m^3.

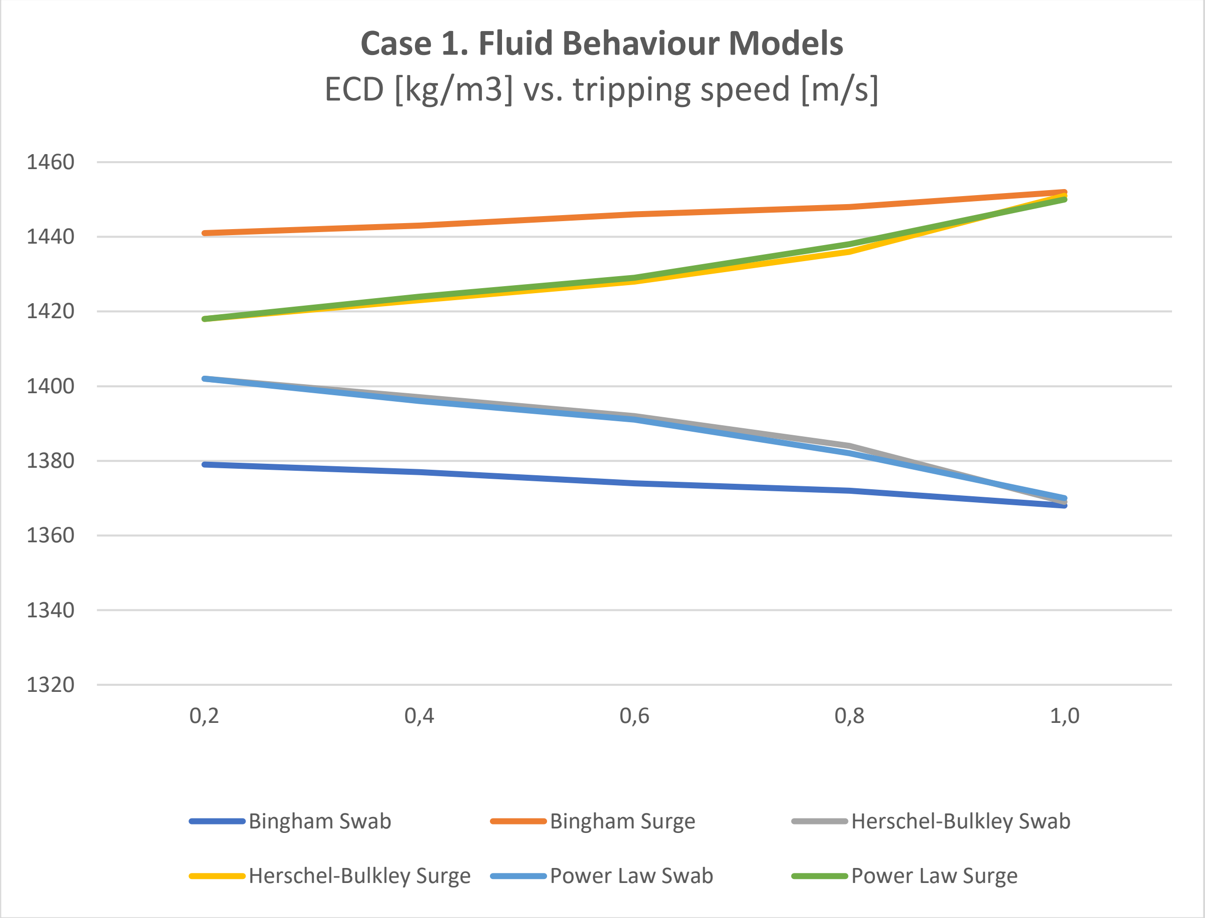


Figure 16: Case 1. Fluid Behaviour models for surge and swab

Bingham Plastic

The Bingham Plastic results for changes in ECD is much higher than the others, making the Bingham Plastic model the safer choice, but the difference between the results and the actual tripping data is much higher for Bingham plastic than it is for the others. The ECD from the Bingham Plastic model at 0.4 m/s is 12 kg/m^3 lower than the actual data, compared to Herschel-Bulkley and Power Law that is 8 and 7 kg/m^3 higher respectively. This over-estimation of surge and swab pressures will cost more time and money than necessary, making the Bingham Plastic model poor in the attempt to decrease non-productive time.

Herschel-Bulkley and Power Law
The ECD results from Power Law and Herschel-Bulkley are approximately the same, where the Power Law model provides a slightly, almost insignificant, more favourable result. The small difference between the two models are the yield point, making the Herschel-Bulkley results of changes in ECD slightly higher than for Power Law. The yield point will be discussed further down this chapter. The change in ECD increases significantly for higher velocities, which is a more realistic fluid behaviour in downhole conditions. Still, a prediction with an error of almost 10 kg/m^3 is not ideal. The Herschel-Bulkley and Power Law estimations needs to be considered with a safety margin. The window in this case between pore pressure and formation fracture pressure is high, so plus/minus 10 kg/m^3 in the ECD estimations can safely be considered acceptable. To investigate which of the two models provides the best results, the further fluid property sensitivity study will be explored with all three models.

5.1.2 Density

The mud density in case 1 is originally set to 1410 kg/m^3. The density was altered in WellPlan, from 1400 to 1420 kg/m^3, with a factor of 5, using Herschel-Bulkley, Power Law and Bingham Plastic. For simplicity, only the swab effect is studied. This well allows ECD above the pore pressure value of 1130 kg/m^3, so all the results are within the acceptable window.

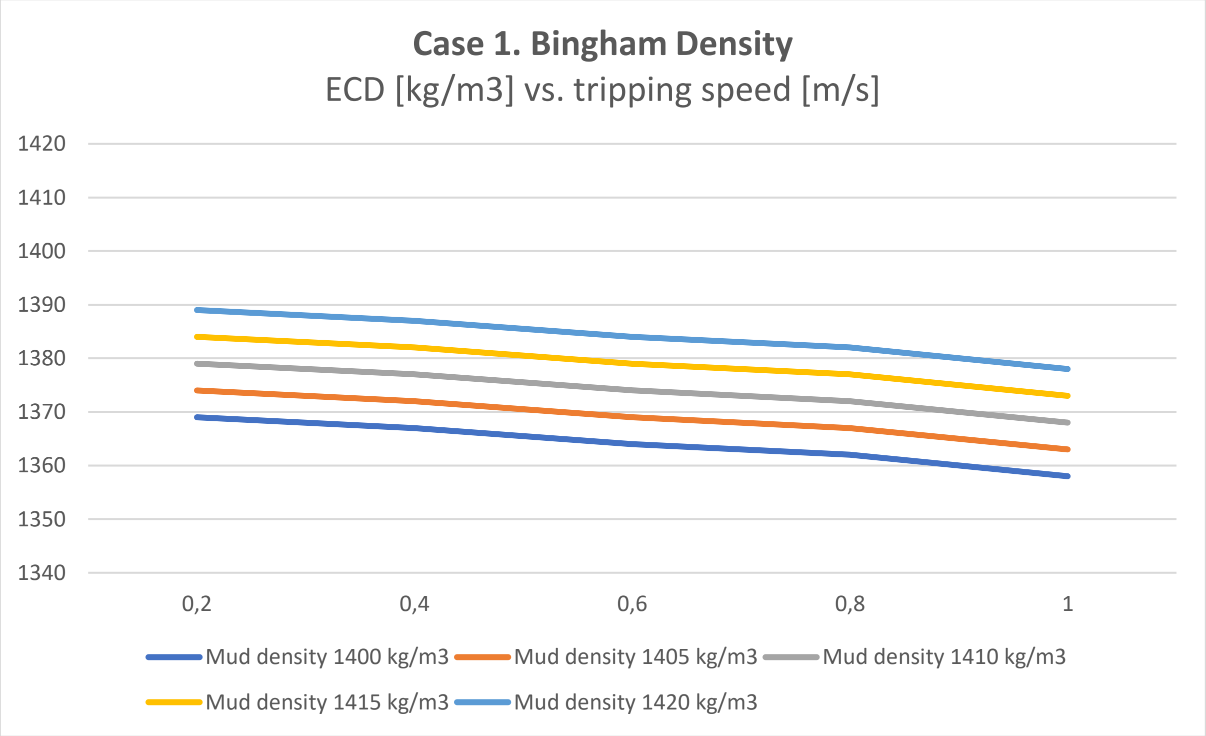


Figure 17: Case 1. Bingham Density sensitivity

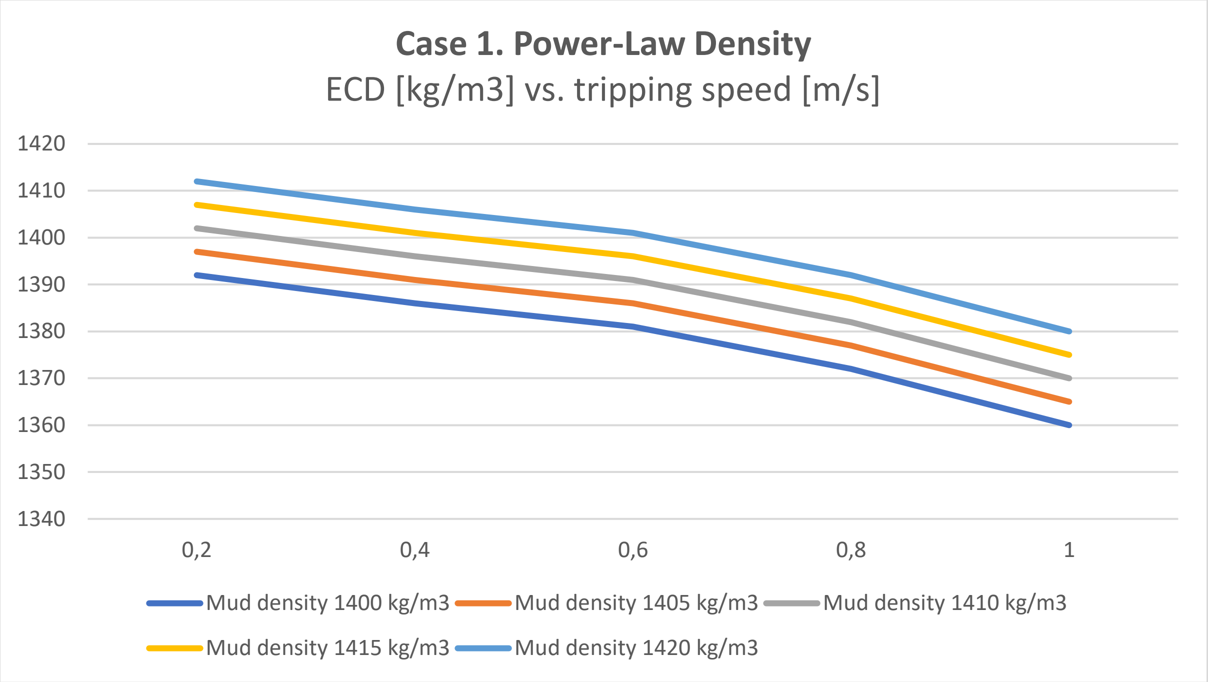


Figure 18: Case 1. Power-Law Density sensitivity

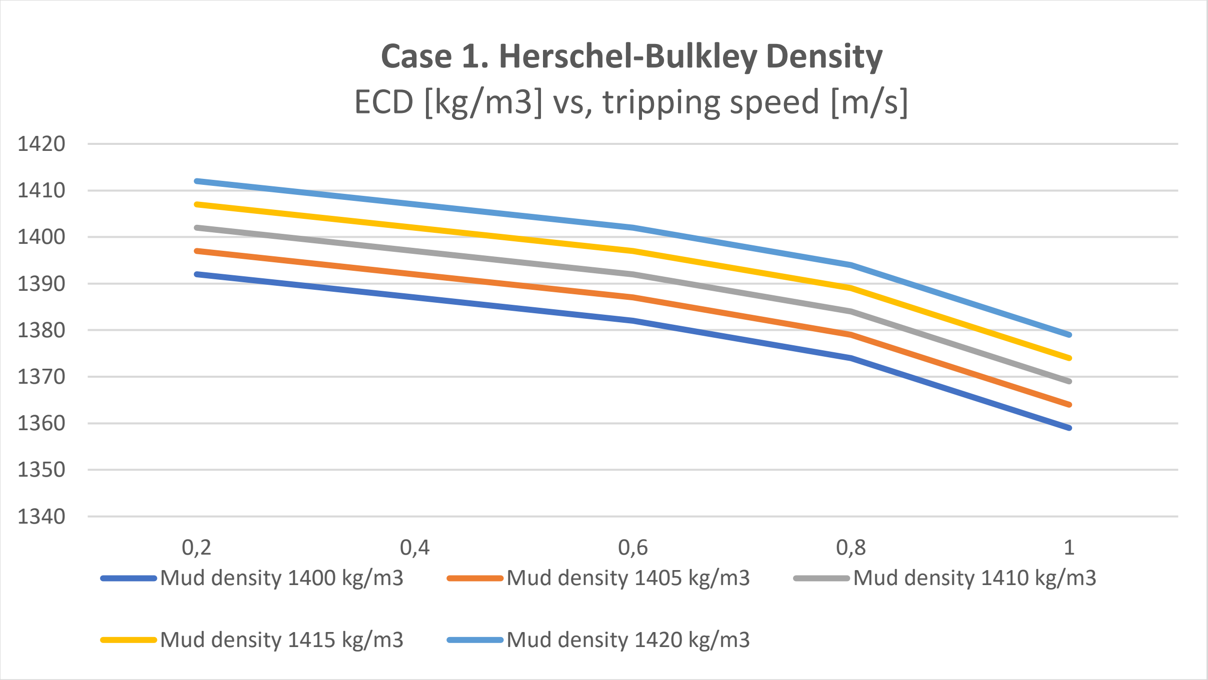


Figure 19: Case 1. Herschel-Bulkley Density sensitivity

The change in ECD when altering the mud density in WellPlan is linearly with the density added or removed from the original density. No difference is detected between the models. Changing the surface mud density will not affect the total decrease or increase in ECD when tripping out or in, hence not affect the pressure changes in a significant matter, according to the WellPlan results. If the estimated ECD for a tripping out operation is close to the pore pressure, an increase of the mud density will be recommended, but the total loss of the ECD would be approximately the same.

5.1.3 Plastic Viscosity

The mud plastic viscosity in this case is 42.43 cp. Normally, the plastic viscosity of oil based drilling muds rarely exceeds 50 cp. The plastic viscosity changes in this sensitivity study is unrealistically high, mainly for investigating purposes. The plastic viscosity can be changed directly in WellPlan by using the Bingham Plastic model. As mentioned in chapter 3, the Bingham Plastic model does not take into consideration the pseudoplastic behaviour of the drilling mud. For the Power Law and Herschel-Bulkley model, the plastic viscosity can only be altered by two pseudoplastic values, the constants n (flow behaviour index) and K (consistency factor). The values for n and K are 0.79 and 0.1846 Pa s^n respectively.

Bingham Plastic

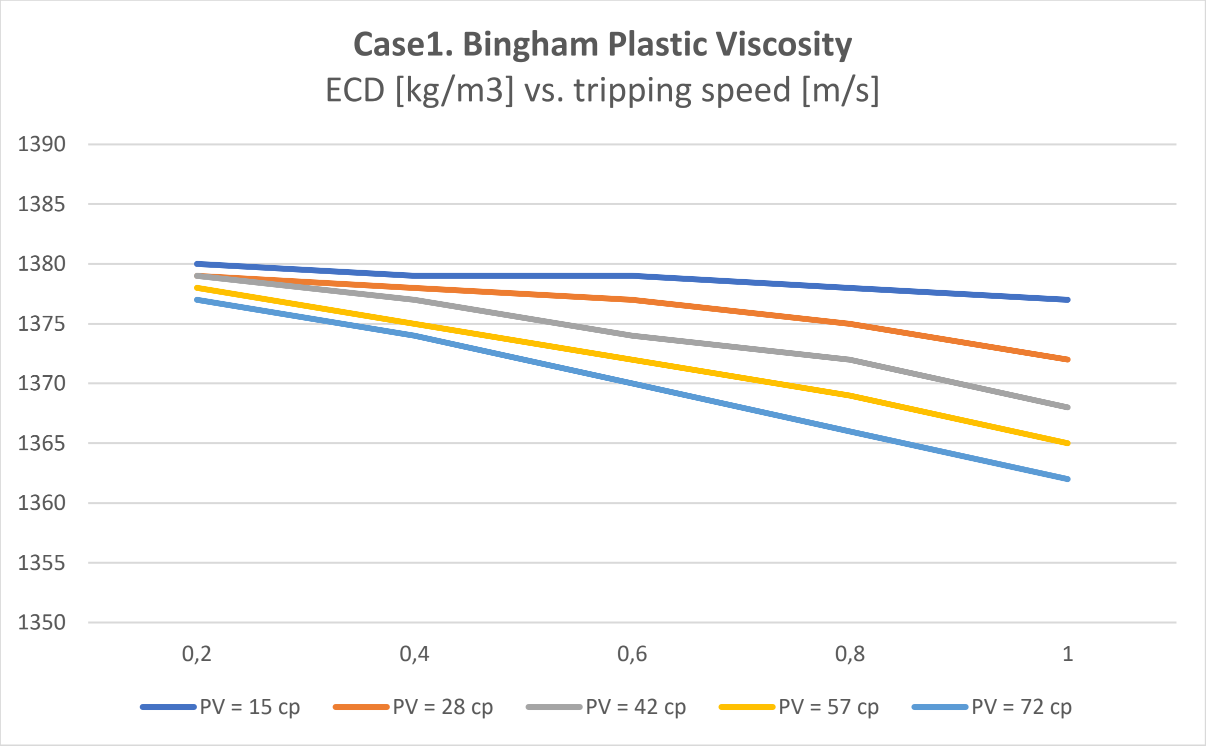


Figure 20: Case 1. Bingham Plastic Viscosity sensitivity

The plastic viscosity clearly has some effect on the surge and swab effects. The trend is obvious, increased viscosity will increase the pressure loss from swabbing, even more so for high velocities. Thus, the ECD is extremely low, and the Bingham Plastic model does not provide good data to estimate surge and swab. However, it provides a good picture of the viscosity effect on ECD. For a better estimate, the plastic viscosity sensitivity study is executed using the pseudoplastic values of Power-Law and Herschel-Bulkley.

Power Law

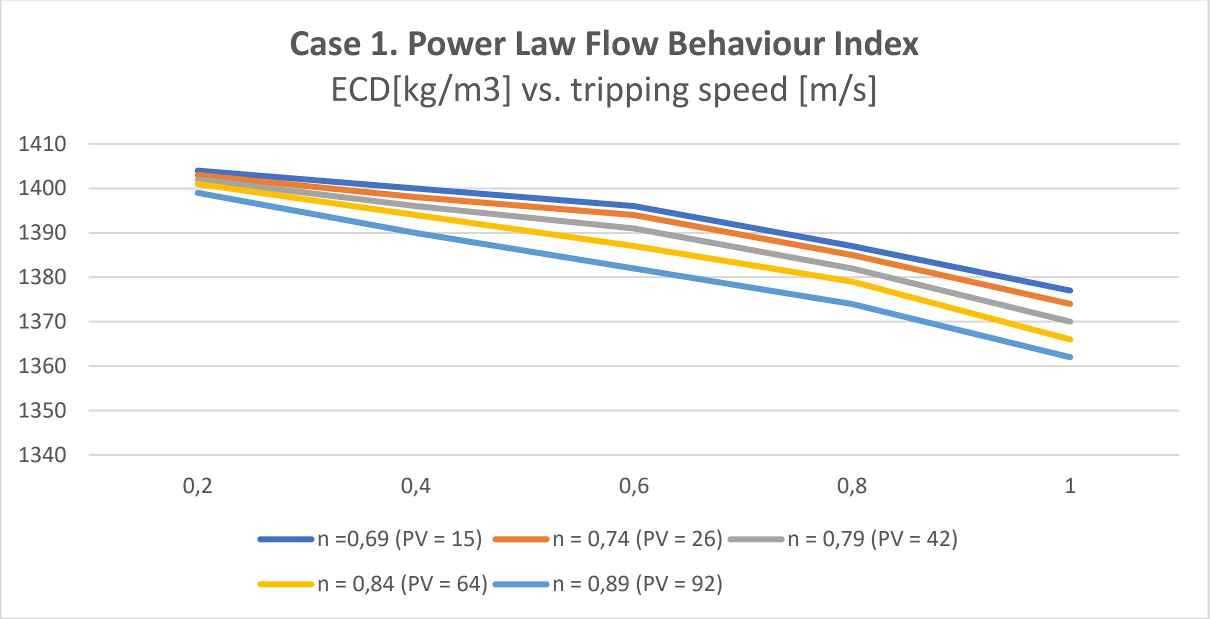


Figure 21: Case 1. Power Law Flow Behaviour Index sensitivity

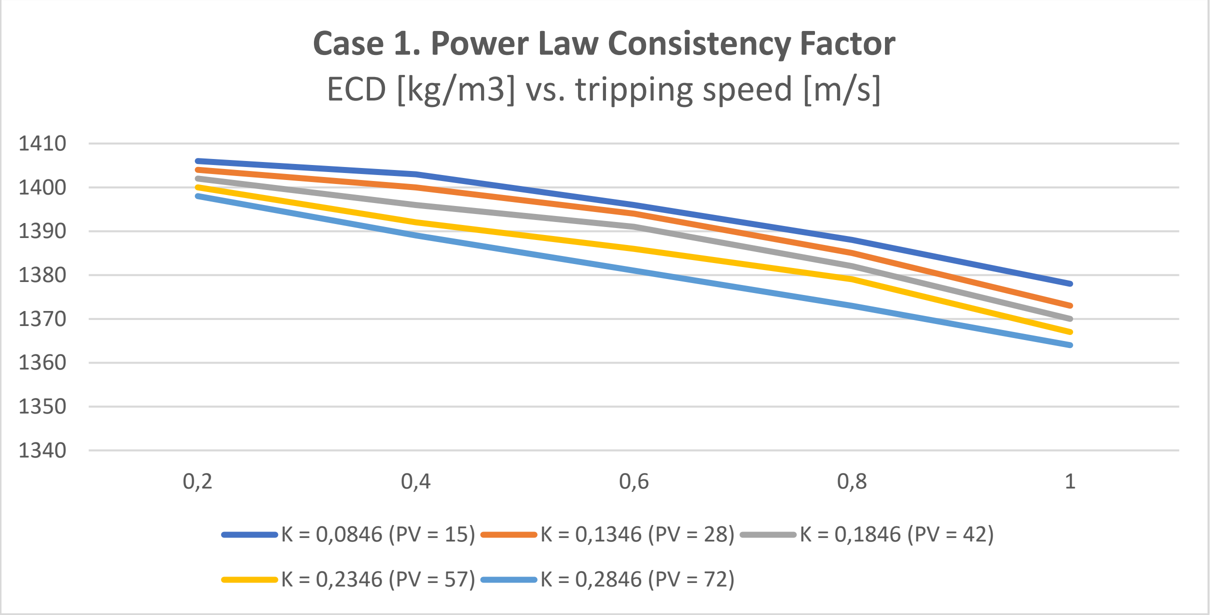


Figure 22: Case 1. Power Law Consistency Factor sensitivity

Both the flow behaviour index and the consistency factor is changed with a factor of 0.05. By when the two constants increases, the plastic viscosity of the mud also increases. The plastic viscosity is more sensitive to changes in the flow behaviour index, causing the plastic viscosity to reach a value twice as high as the actual plastic viscosity. For the high values of n, the fluid is estimated towards Newtonian behaviour, which is not the real case for any drilling fluid. The trend from the Power Law results is the same as for Bingham, the PV should not be too high, when the surge and swab effect will increase. Thus, the Power Law results for plastic viscosity indicates that the effect of velocity increase is not of the magnitude according to the Bingham Plastic model.

Herschel-Bulkley

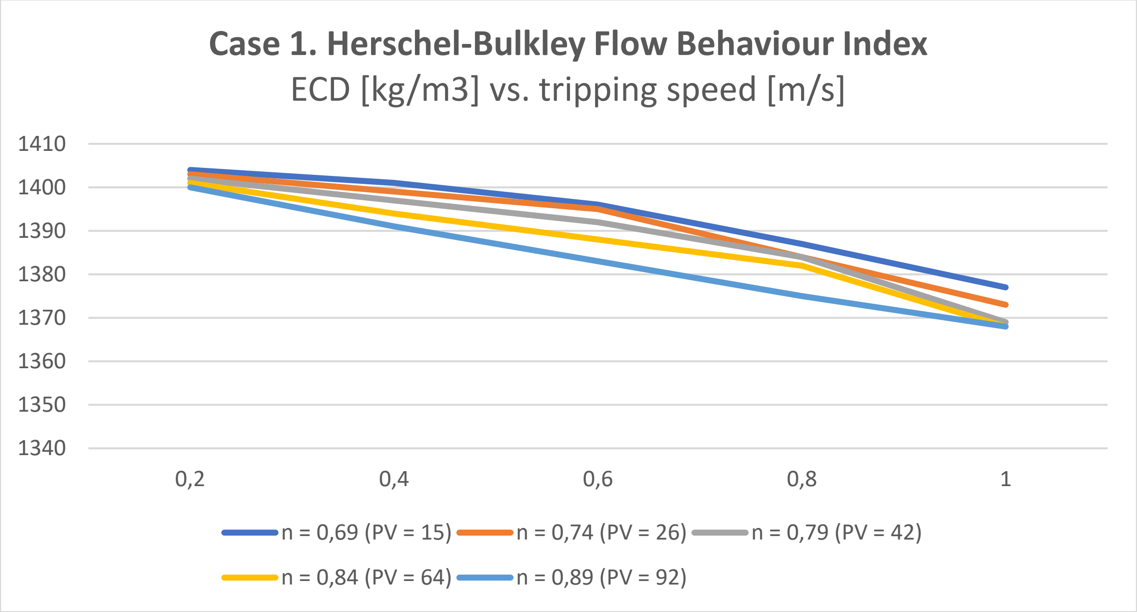


Figure 23: Case 1. Herschel-Bulkley Flow Behaviour Index sensitivity

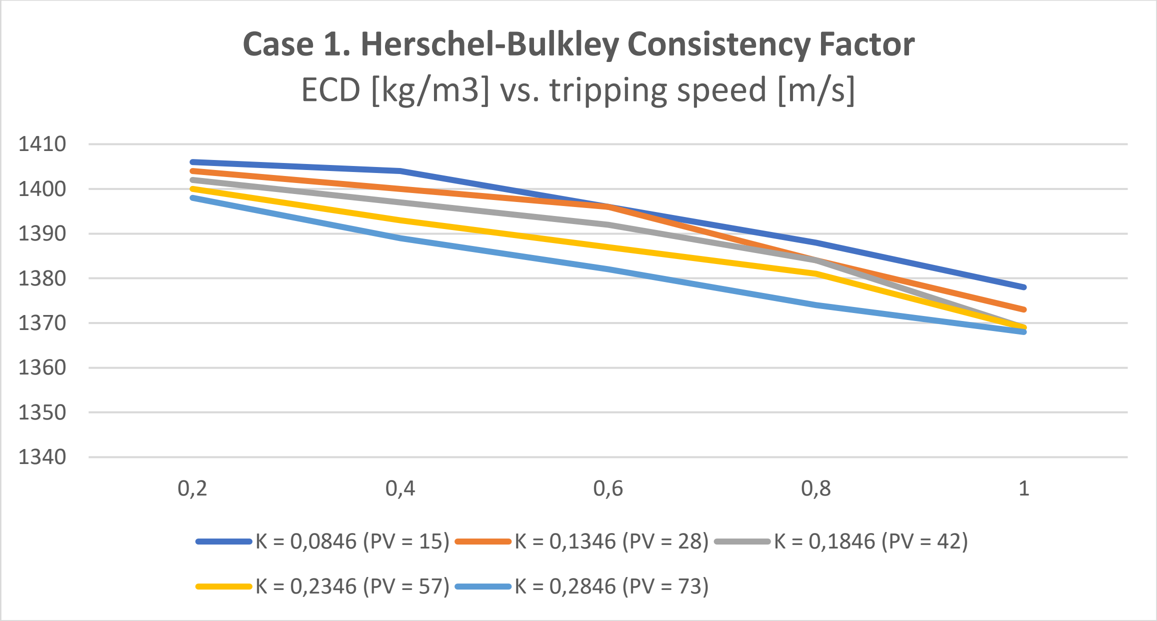


Figure 24: Case 1. Herschel-Bulkley Consistency Factor sensitivity

Doing the same alterations for n and K using the Herschel-Bulkley model, the same trend is visible, namely that the ECD change increases with increased PV. The main difference between Power Law and Herschel-Bulkley for plastic viscosity is that for Herschel-Bulkley, the ECD is slightly higher for high viscosity at high velocity. Thus, not the high velocity of 1.0 m/s nor the high plastic viscosity values are realistic, so the variance of ECD for the realistic values are approximately the same. One can conclude that for surge and swab effects, low plastic viscosity is favourable, and the magnitude of ECD changes by small alterations in plastic viscosity is relatively minor, thus slightly higher than for the density.

5.1.4 Yield Point

As described in chapter 3, the yield point is not taken into account for the Power-Law model. Alterations of the yield point, which originally is set to 11.903 lbf/100ft^2, did not affect the ECD results for the Herschel-Bulkley results. This indicates a minor significance of the yield point of the drilling mud for this operation. For the Bingham Plastic model on the other hand, the yield point is a substantial value for the calculations.

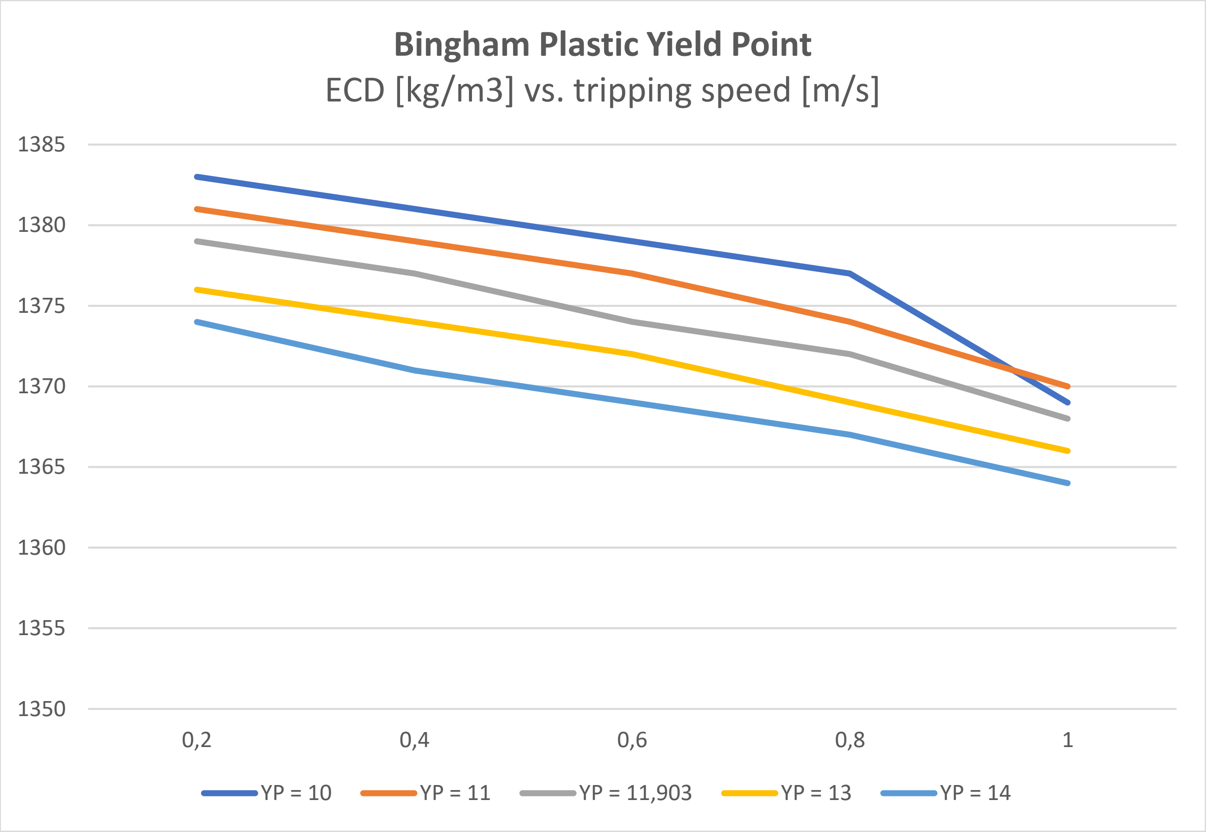


Figure 25: Case 1. Bingham Plastic Yield Point sensitivity

By changing the yield point with a factor of approximately 1, the increase in surge and swab effects are of significance. It is a known fact that the yield point causes a pressure change immediately when the fluid starts to move. Even though the Bingham Plastic estimations are not favourable, it shows that low yield point is favourable when tripping, independent of the velocity.

5.1.5 Bottom Hole Assembly Dimensions

For simplicity, the BHA in case 1 only consist of the bit, a measurement while drilling tool (MWD), and a heavy weight drill pipe. In real drilling operations, several more components are added to the BHA, making it several meters longer, and with different diameters, also impacting the pressure loss over the BHA. By altering the dimensions of the MWD-tool, these effects can be observed, but then with a level of uncertainty due to the simplifications. The MWD is originally 2.5 meters long, with an outer diameter of 9.5 inch, and the weight of the tool is approximately 16 times heavier than the drill pipe. By adding length and diameter, the weight on bit will also increase.

Length

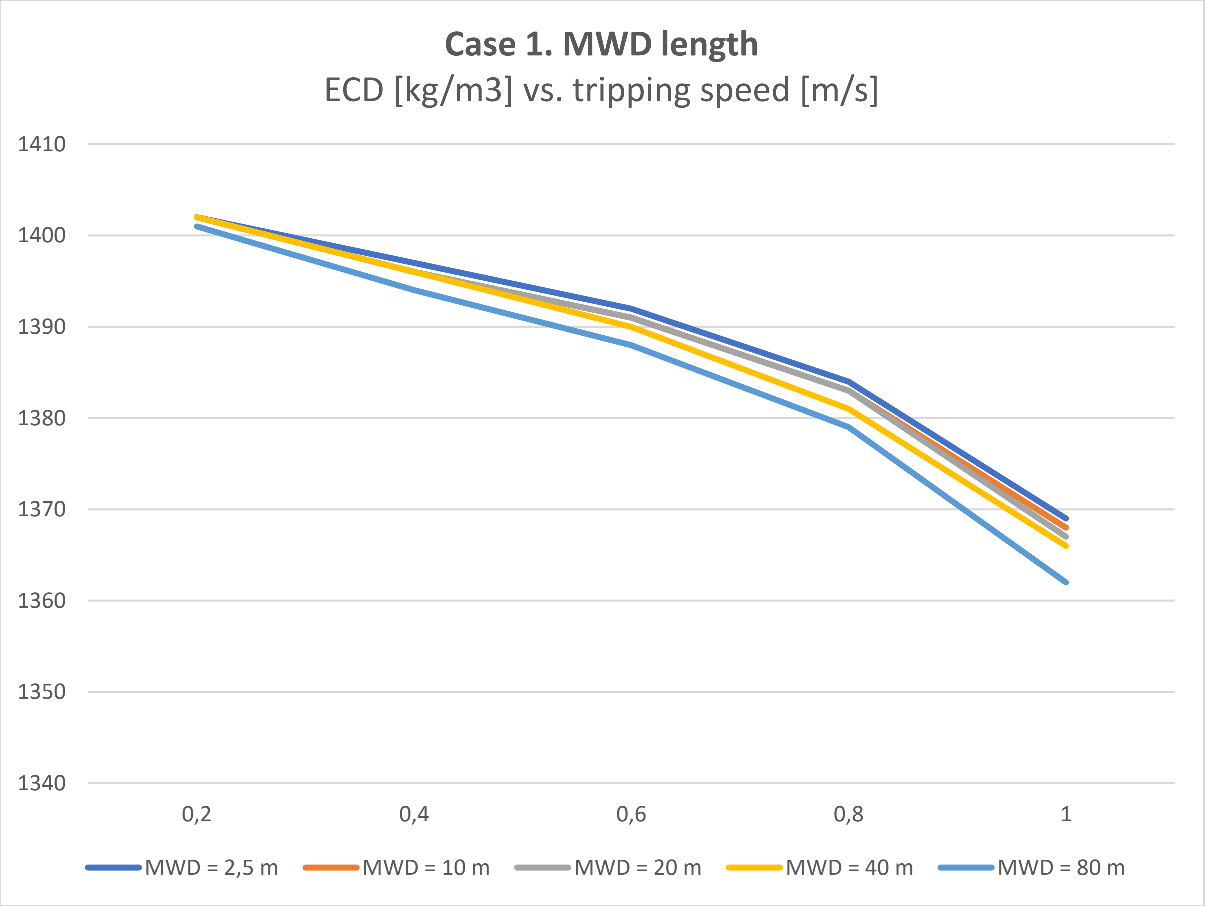


Figure 26: Case 1. MWD Length sensitivity

Quite large changes had to be made to the length of the MWD to observe significant changes in ECD, thus the actual BHA in a real drilling operation may be several hundred meters long. It is a given that the longer the BHA is, the less room for the fluid to flow, and the higher the surge and swab effect. This is also a testify to the annulus clearance effect on surge and swab, which will be discussed further down this chapter.

Diameter

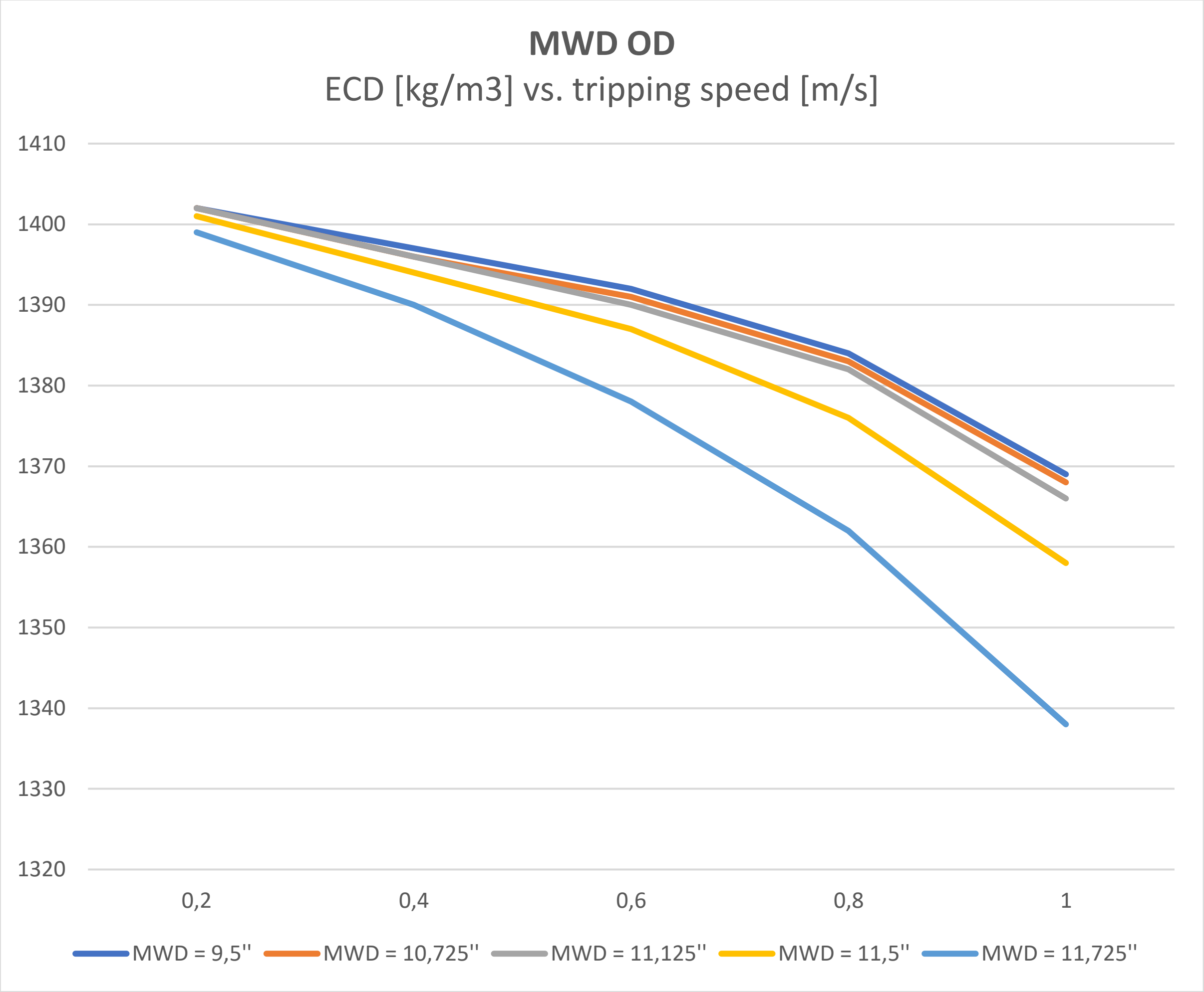


Figure 27: Case 1. MWD Diameter sensitivity

The diameter change of MWD seems to be extreme at high velocities. Especially when the difference between the bit diameter and the MWD diameter is small. Minor changes in the MWD diameter did not change the ECD much, but the closer it got to the bit diameter, the faster it escalated. This proves that the pressure changes around the bit and BHA are of great magnitude, and it is important to take account for this in surge and swab estimations. The BHA should be as small as possible to decrease the pressure changes.

5.1.6 Annular Clearance

To analyse the impact on surge and swab by annular clearance, two different scenarios where set up. One by altering the drill pipe outer diameter, and one by changing the original bit and open hole diameter. For altering the open hole section, the casing also had to be expanded to the same diameter as the bit.

Scenario 1, where the drill pipe outer diameter was reduced

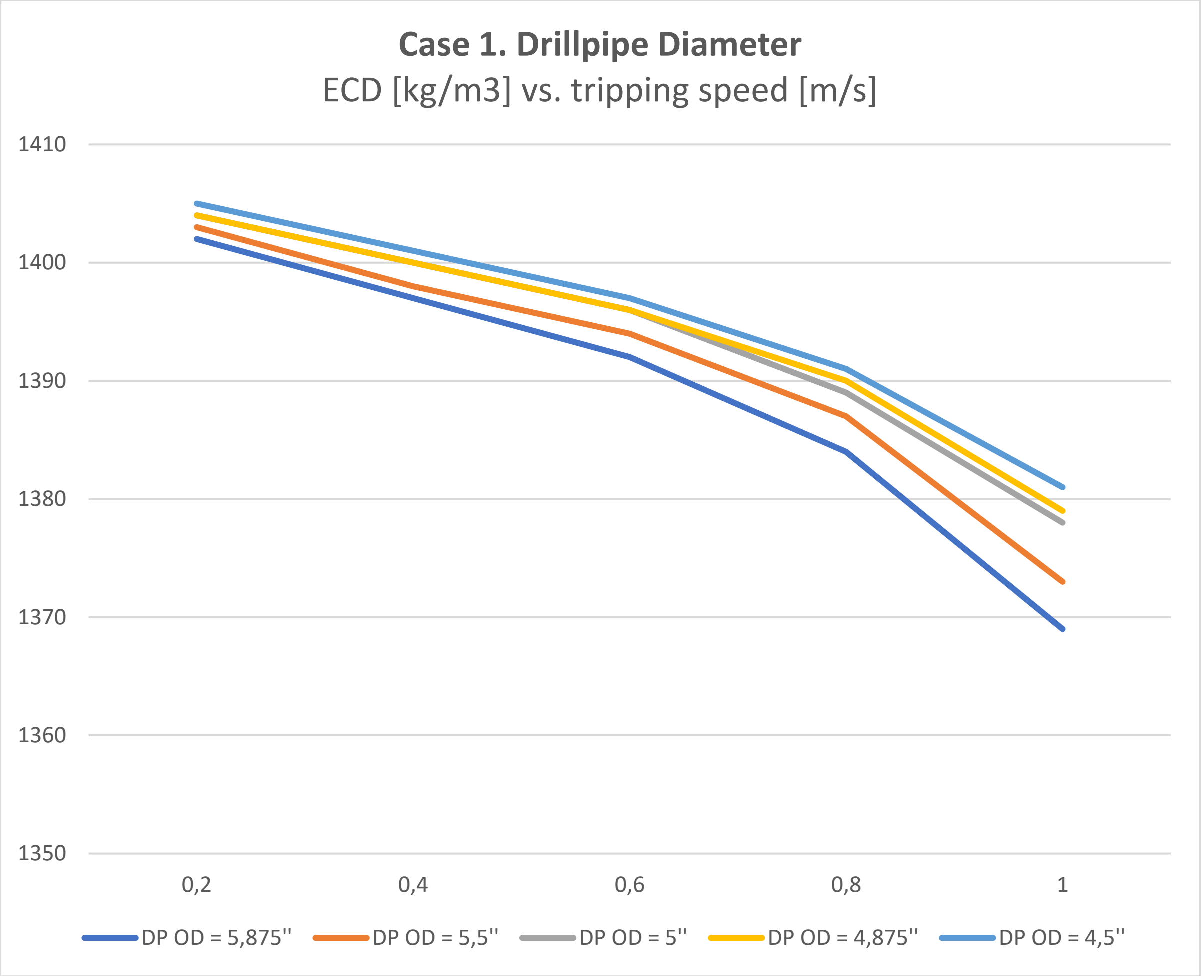


Figure 28: Case 1. Drill Pipe Diameter sensitivity

Scenario 2, where the bit and open hole diameter was changed

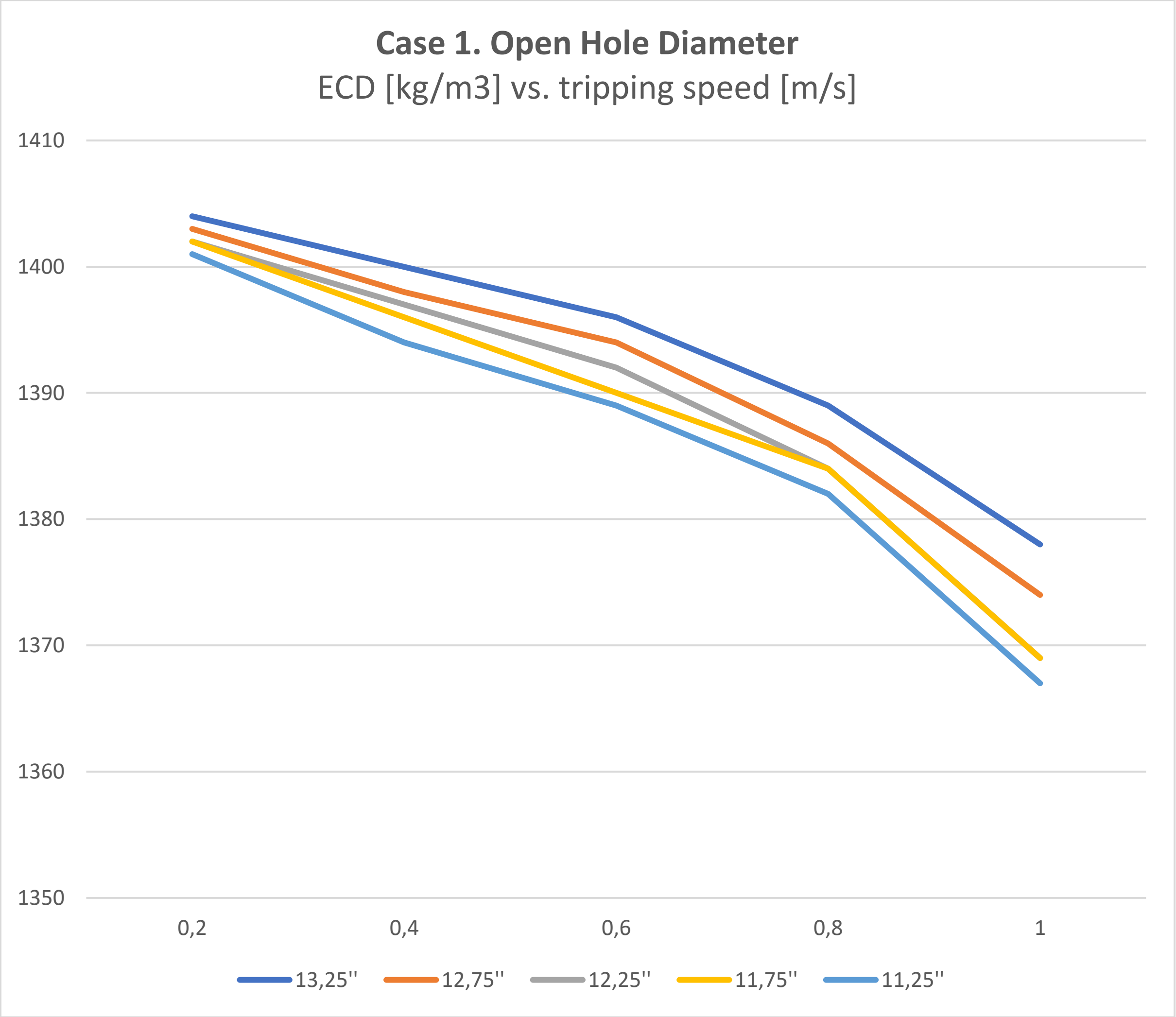


Figure 29: Case 1. Open Hole Diameter sensitivity

The results from the two scenarios for enhanced annular clearance are approximately the same. Both scenarios make more room for the fluid to flow, and one inch decrease of the drill pipe diameter provides the same increase in ECD for 0.4 m/s as for one inch increase in the open hole. In the case of decreased drill pipe, there is a small favourable difference in ECD compared to scenario 2 at high velocity. This can be explained by the pressure loss over the bit, which is larger when the bit is larger.

5.2 Case 2 Results

5.2.1 Fluid Flow Behaviour Models

For case 2, no actual tripping data is provided, so no comparison can be done in this analysis. This case is much more complicated than case 1, due to the long horizontal open hole section. The window between pore pressure and formation fracture pressure is narrow, 900 and 1600 kg/m^3 respectively, so careful considerations need to be made, and it is of great importance to estimate surge and swab pressures as accurate as possible.

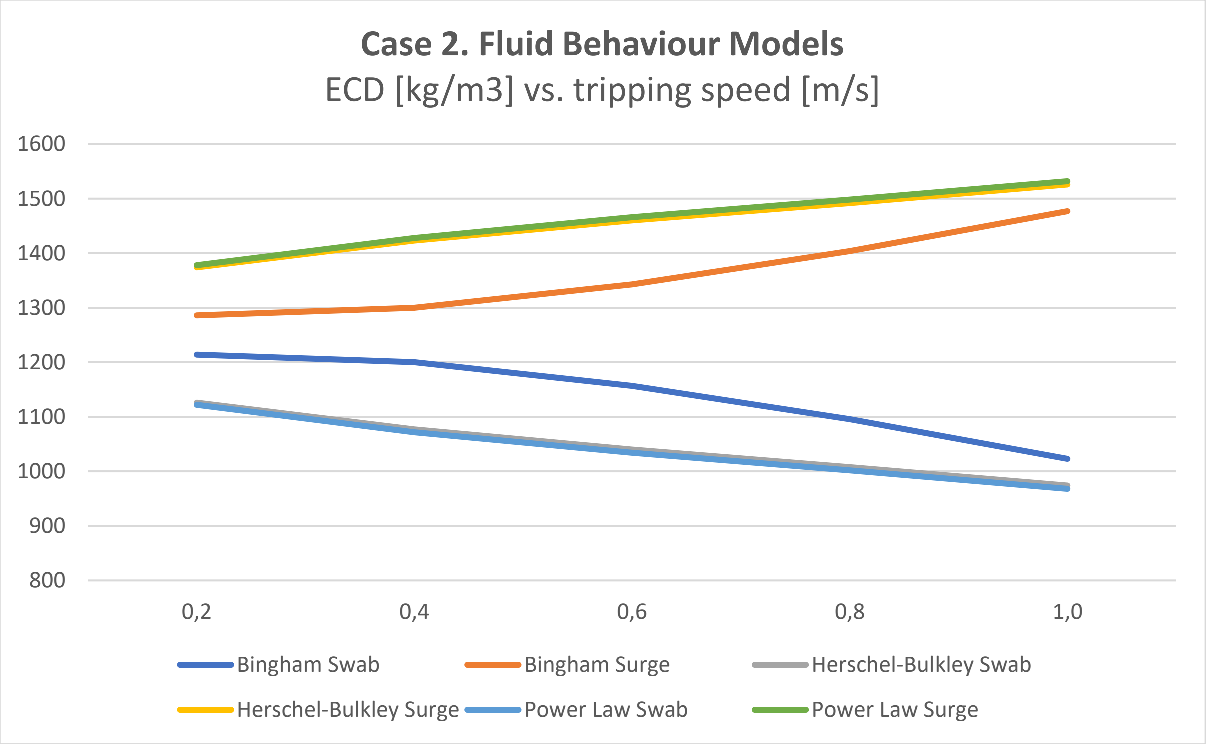


Figure 30: Case 2. Fluid Behaviour Models for surge and swab

Bingham Plastic

In this case, the Bingham plastic model provides the most desired results. The ECD is actually closer to the surface mud density, opposite of case 1. Knowing the narrow pressure window, and potentially dangerous situations that may occur if the surge and swab effects are underestimated, combined with the uncertainties of the Bingham calculations, it would be potentially dangerous to trust these estimations of ECD.

Power Law and Herschel-Bulkley

Also in this case, the Power Law model and Herschel-Bulkley model provides very similar results for the ECD values. If the same is true for these estimations as for case 1, where the actual ECD changes was higher than estimated, the tripping operation would provide pressure changes very close to the pressure limits.

5.2.2 Density

The mud density in case 2 is originally set to 1250 kg/m^3. The density was altered in WellPlan, from 1240 to 1260 kg/m^3, with the same factor of 5, using Herschel-Bulkley, Power Law and Bingham Plastic, same as for case 1. For simplicity, only the swab effect is studied. This well allows ECD above the pore pressure value of 900 kg/m^3.

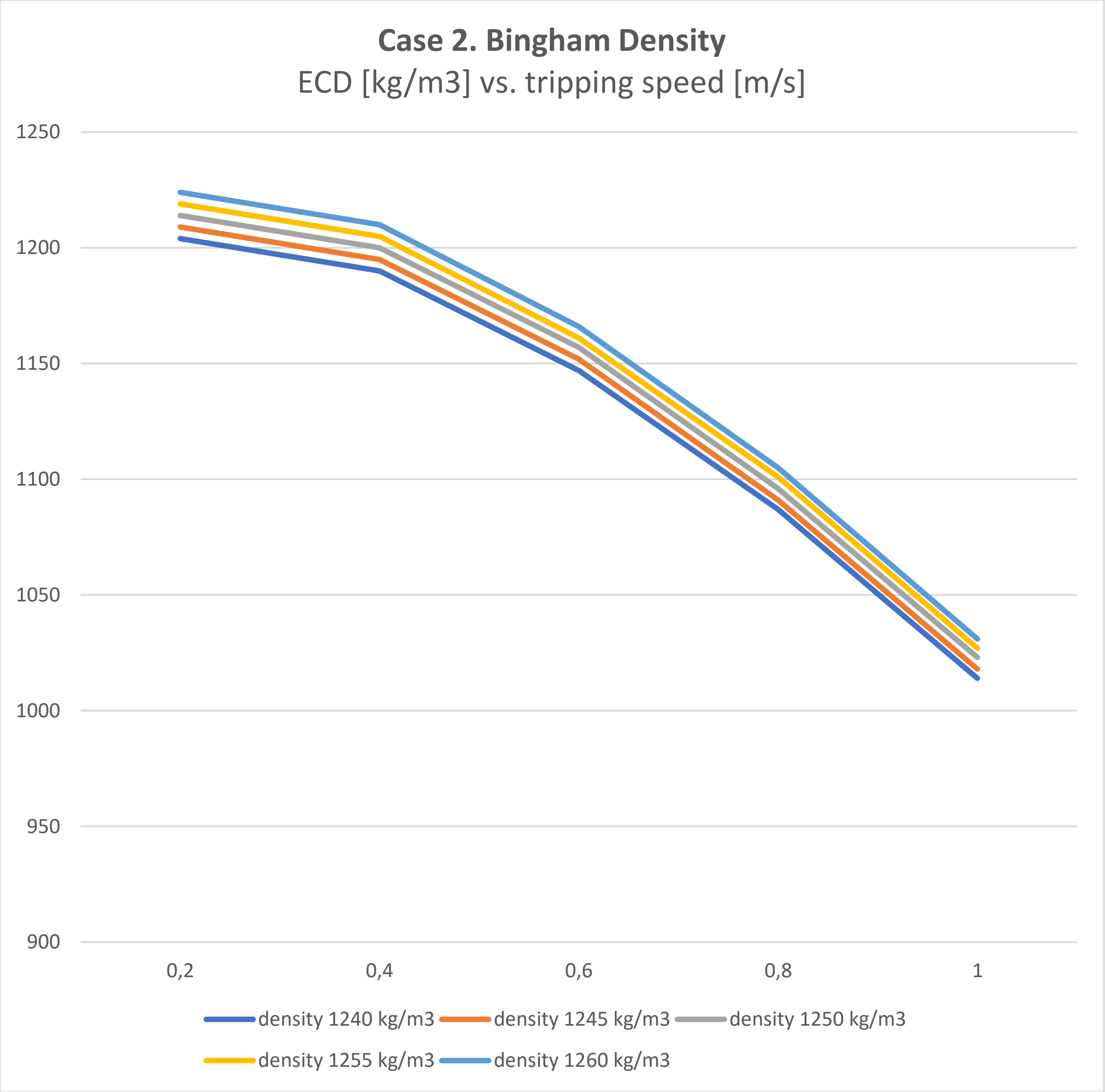


Figure 31: Case 2. Bingham Plastic Density sensitivity

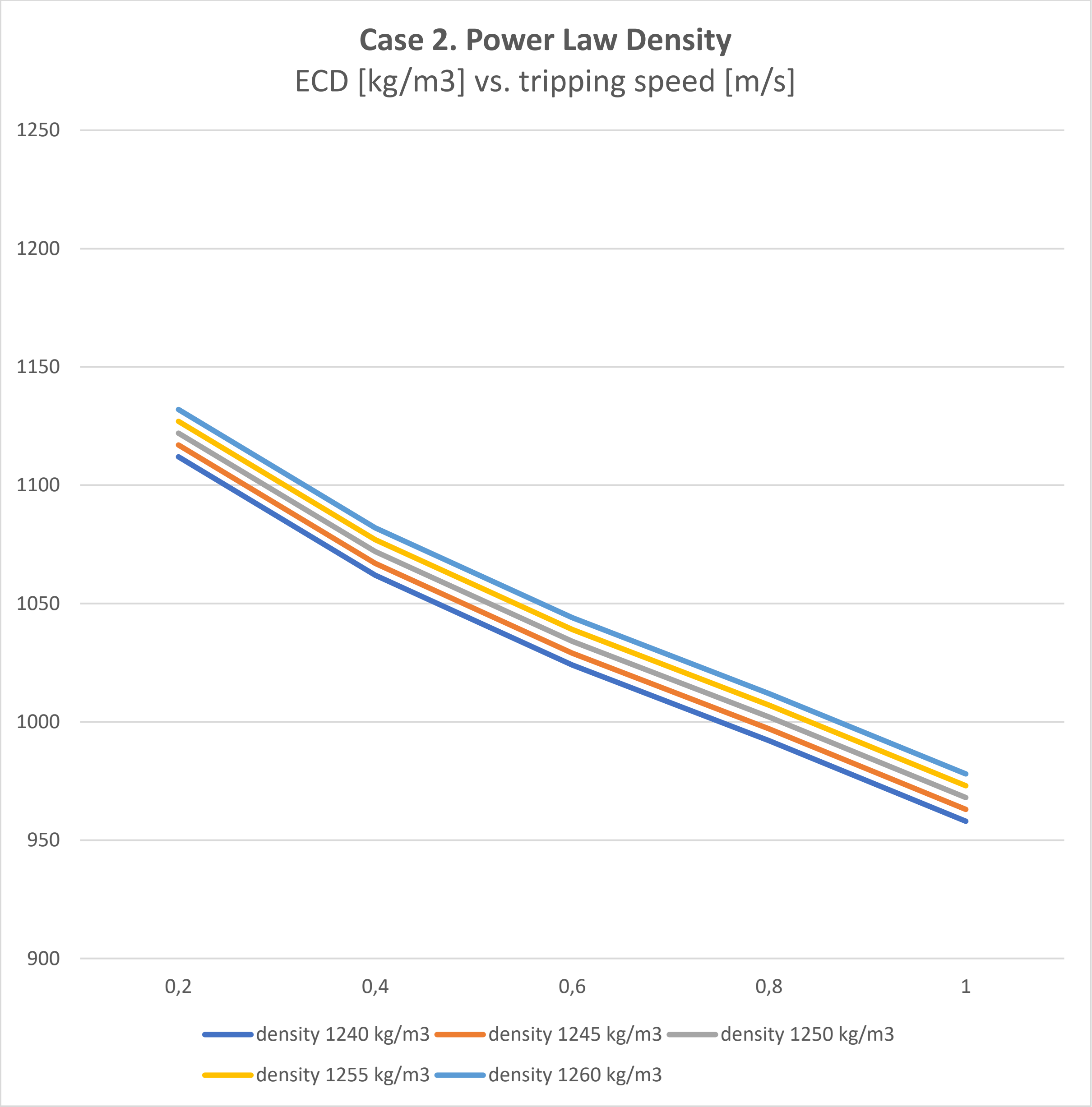


Figure 32: Case 2. Power Law Density sensitivity

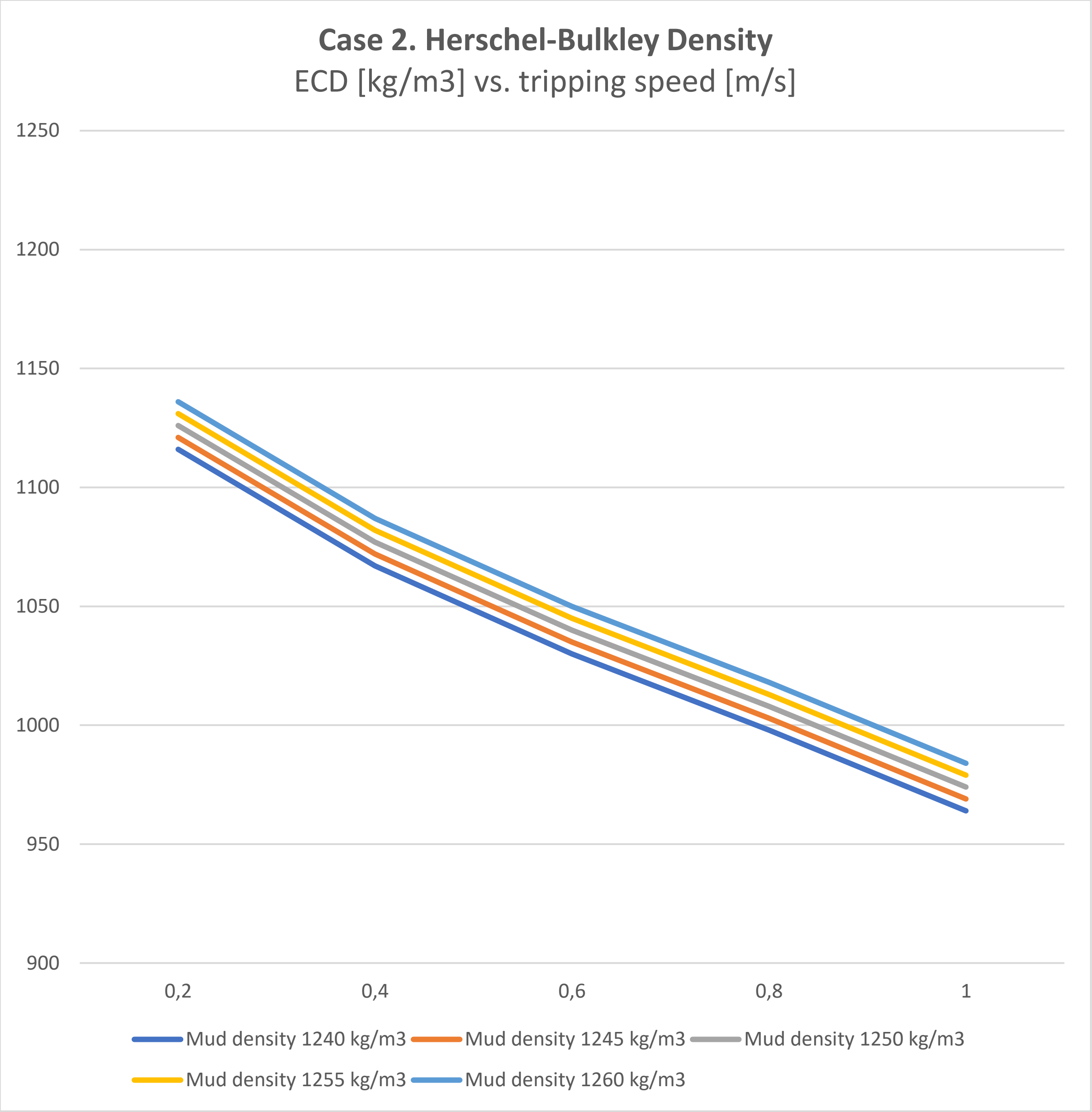


Figure 33: Case 2. Herschel-Bulkley Density sensitivity

The ECD changes is not quite linearly with changing the surface mud density in the estimations according to the Bingham Plastic estimations. At higher velocities, the change in ECD is a bit smaller than the change made in density. This may indicate that the density has a slightly smaller effect on surge and swab according to Bingham. Thus, this is only true at 0.8 and 1.0 m/s, which is not a realistic tripping speed. Both the Power Law and Herschel-Bulkley model indicates the same as in case 1, the ECD change is equal to the density change, independent of the velocity.

5.2.3 Plastic Viscosity

The mud plastic viscosity in this case is 12.81 cp. The plastic viscosity of water based drilling muds is normally desired to be as low as possible, and lies somewhere between 10-25 cp. The plastic viscosity changes in this sensitivity study is also unrealistically high for investigating purposes. Using the same procedure as for case 1, the plastic viscosity is altered for the Bingham Plastic model, and the flow behaviour index and the consistency factor are altered for the Power Law and Herschel-Bulkley models. Originally the n is 0.48, and K is 0.9288 Pa s^n.

Bingham Plastic

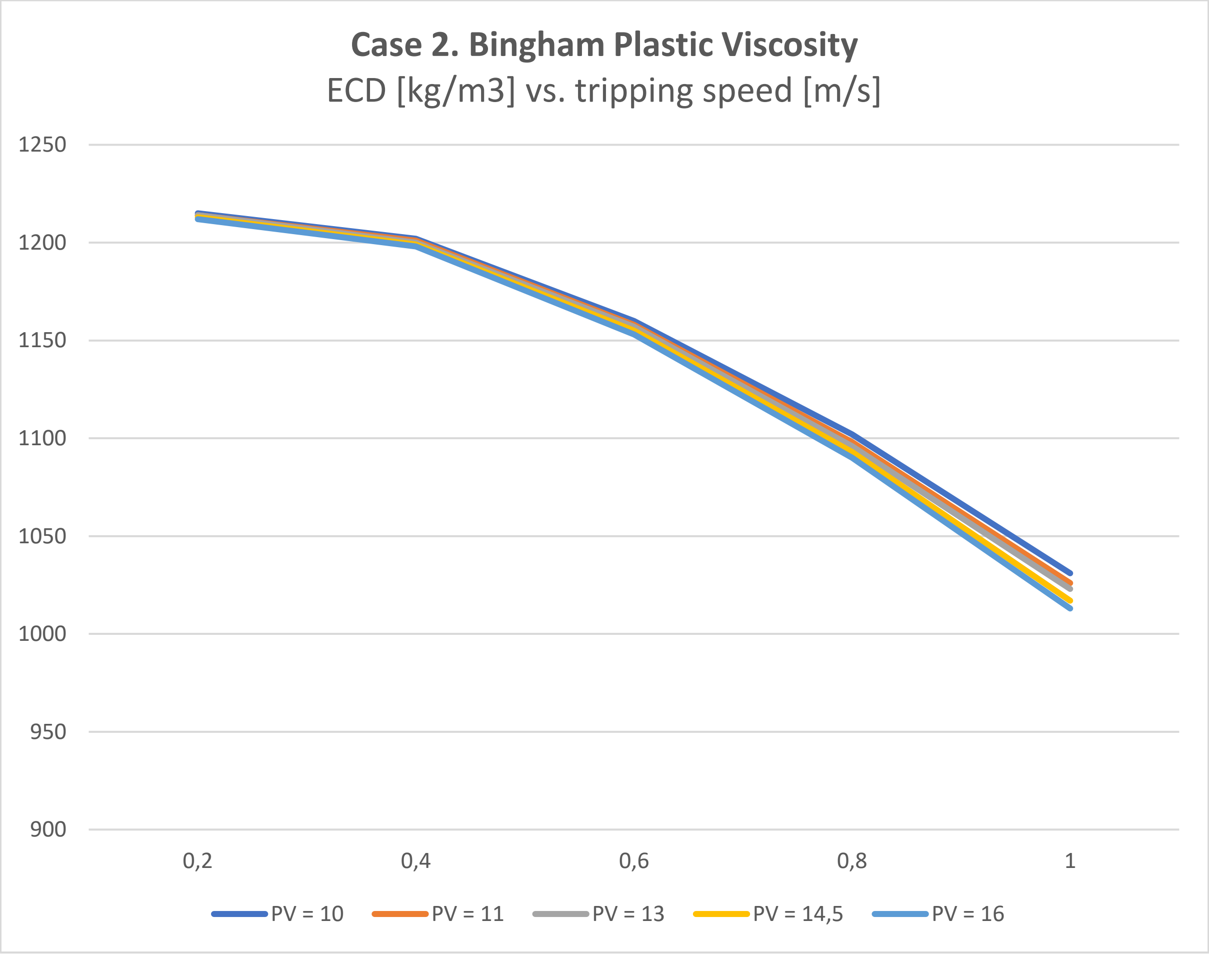


Figure 34: Case 2. Bingham Plastic Viscosity sensitivity

The small changes made in the plastic viscosity did not alter the ECD in a significantly amount at low and normal velocities. The values tested are chosen based on the plastic viscosity values achieved when altering the consistency factor for the Power Law and Herschel-Bulkley model with the predefined value of 0.05. Unlike the analysis in case 1, the plastic velocity changes are more realistic. The effect on surge and swab are here minor, but the tendency is the same, namely that by decreasing the plastic viscosity, the surge and swab effects can be slightly reduced.

Power Law

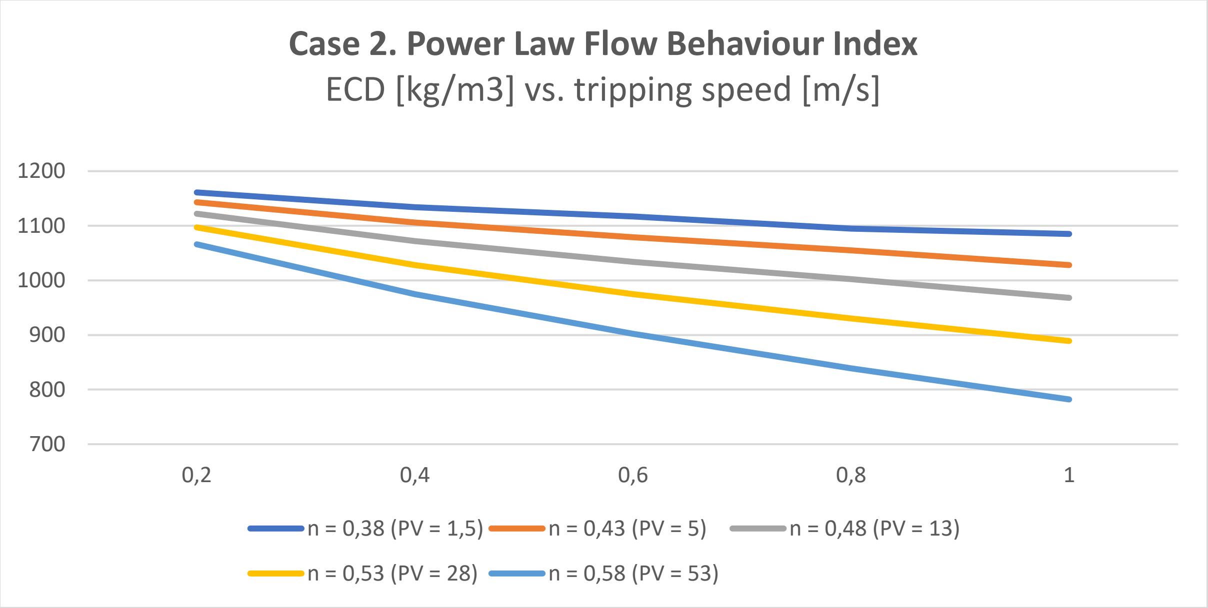


Figure 35: Case 2. Power Law Flow Behaviour Index sensitivity

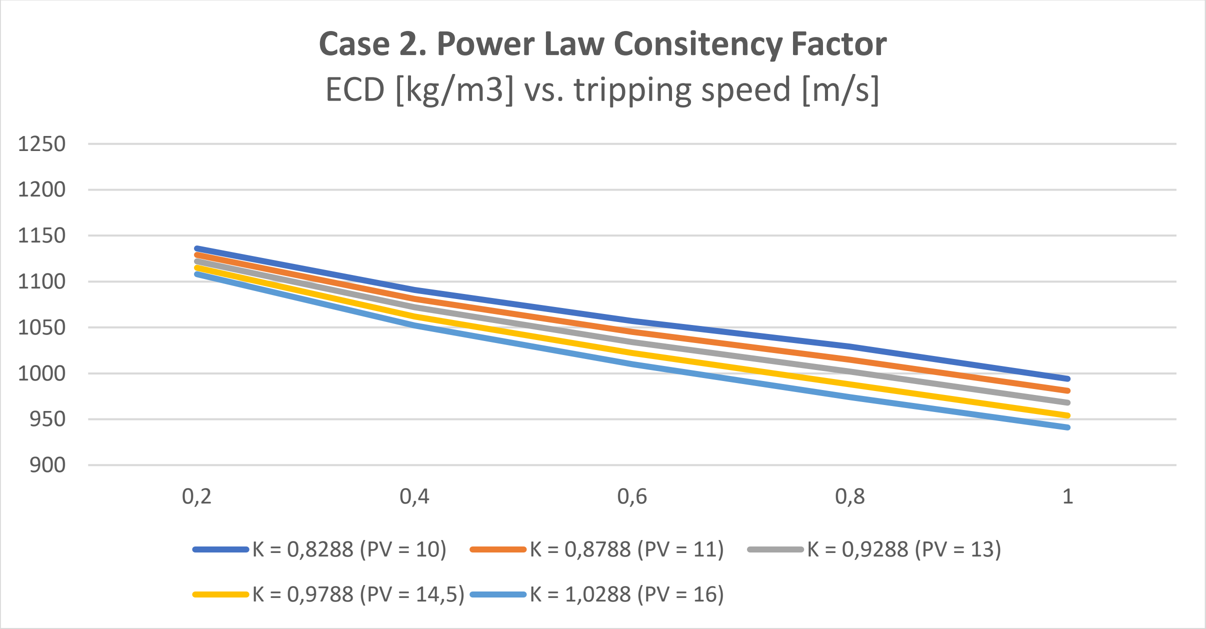


Figure 36: Case 2. Power Law Consistency Factor sensitivity

The plastic viscosity is in this case more sensitive to changes in the flow behaviour index than the consistency factor. The same alterations are done in this case as in case 1, with a factor of 0.05. The Power Law model claims the ECD to be more affected by changes in plastic viscosity than the Bingham Plastic model. At 4 m/s tripping speed, the reduction in plastic viscosity from 13 cp to 10 cp will according to the Power Law estimations enhance the ECD with 19 kg/m^3, while according to the Bingham Plastic results, the same reduction in plastic viscosity will only increase ECD with 2 kg/m^3. The plastic viscosity also seems to be of a much greater importance for case 2 than for case 1.

Herschel-Bulkley

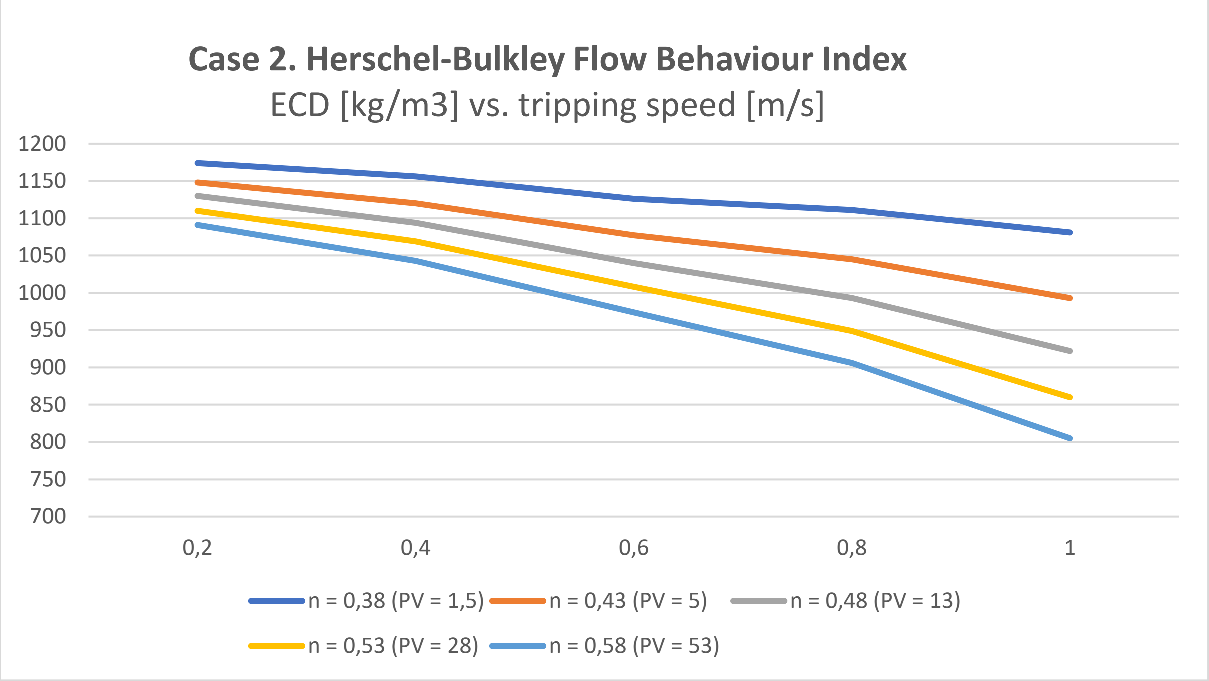


Figure 37: Case 2. Herschel-Bulkley Flow Behaviour Index sensitivity

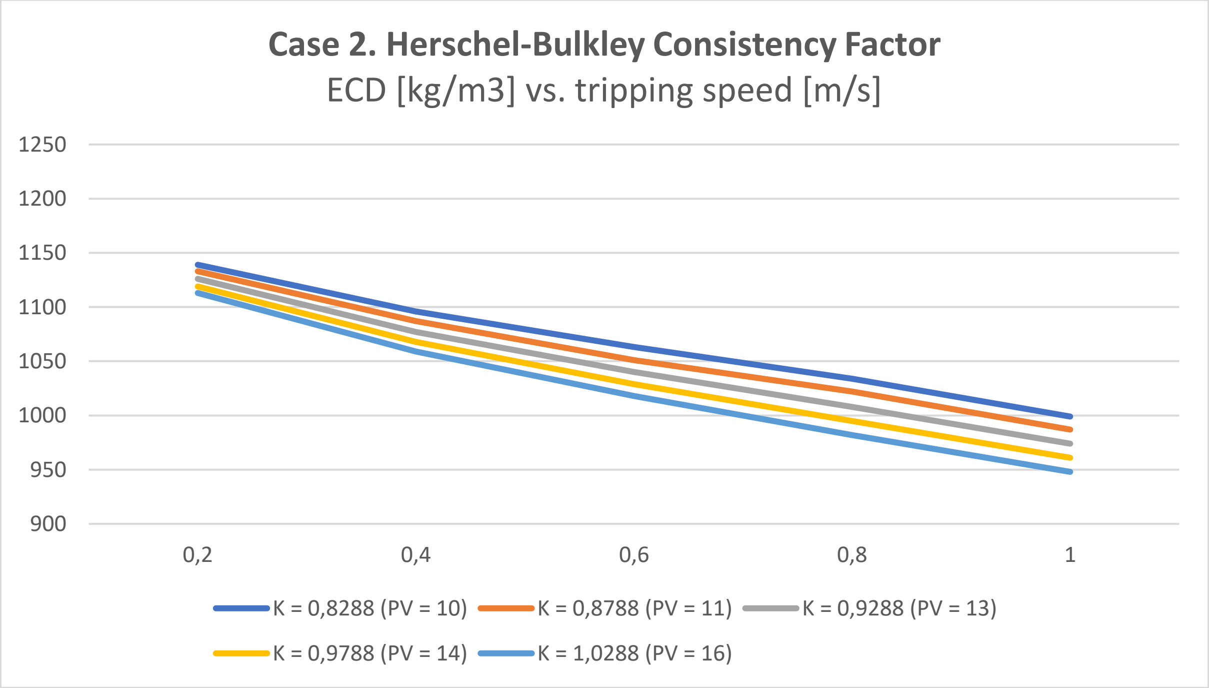


Figure 38: Case 2. Herschel-Bulkley Consistency Factor sensitivity

The Herschel-Bulkley results for plastic viscosity is similar to the Power Law results. The ECD is enhanced with 19 kg/m^3 by reducing the plastic viscosity from 13 to 10 cp for 0.4 m/s tripping speed. This is in this case a significant amount, with the ECD relatively close to the pressure limits, and must be accounted for in surge and swab estimations.

5.2.4 Yield Point

The yield point in case 2 is originally set to 2.265 lbf/100ft^2. Same as for case 1, altering the yield point for the Herschel-Bulkley model did not affect the ECD. The results from changing the yield point with a factor of 1 for each step, are as follows.

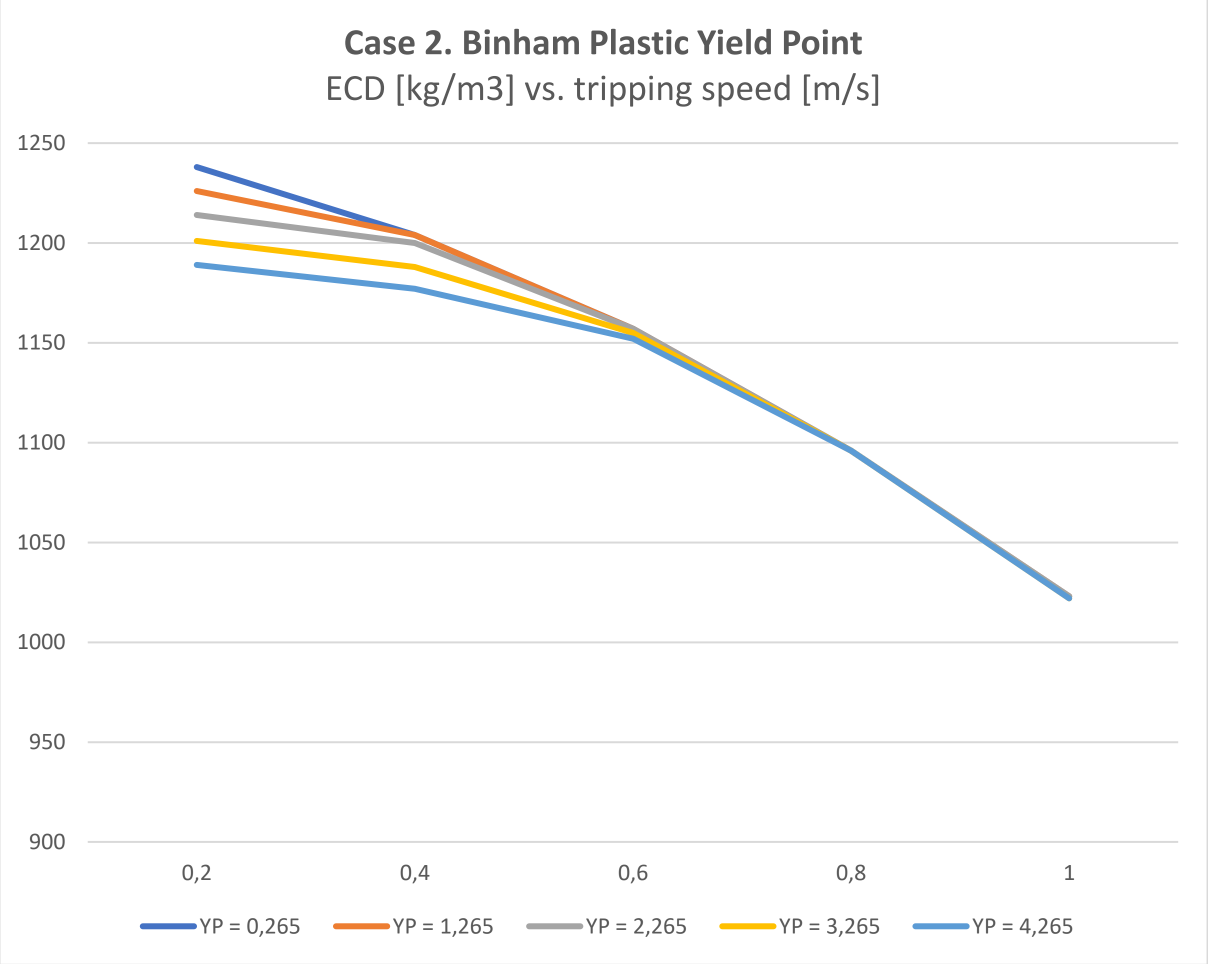


Figure 39: Case 2. Bingham Plastic Yield Point sensitivity

From the theory behind the yield point, it is known that the pressure change caused by the yield point happens immediately when the fluid starts to move. It provides no further pressure change when the velocity increases. The same statement can be made as for case 1, that a low yield point is favourable, but the effect on ECD is minor.

5.2.5 Bottom Hole Assembly Dimensions

The BHA in case 2 consist of only of a drill collar above the bit. This is also not realistic, when stabilizers and other tools should be added to the WellPlan simulations to provide better results in this sensitivity analysis. The drill collar is 27 meters long, with an outer diameter of 6.75 inch, and a weight almost five times as high as the drill pipe.

Length

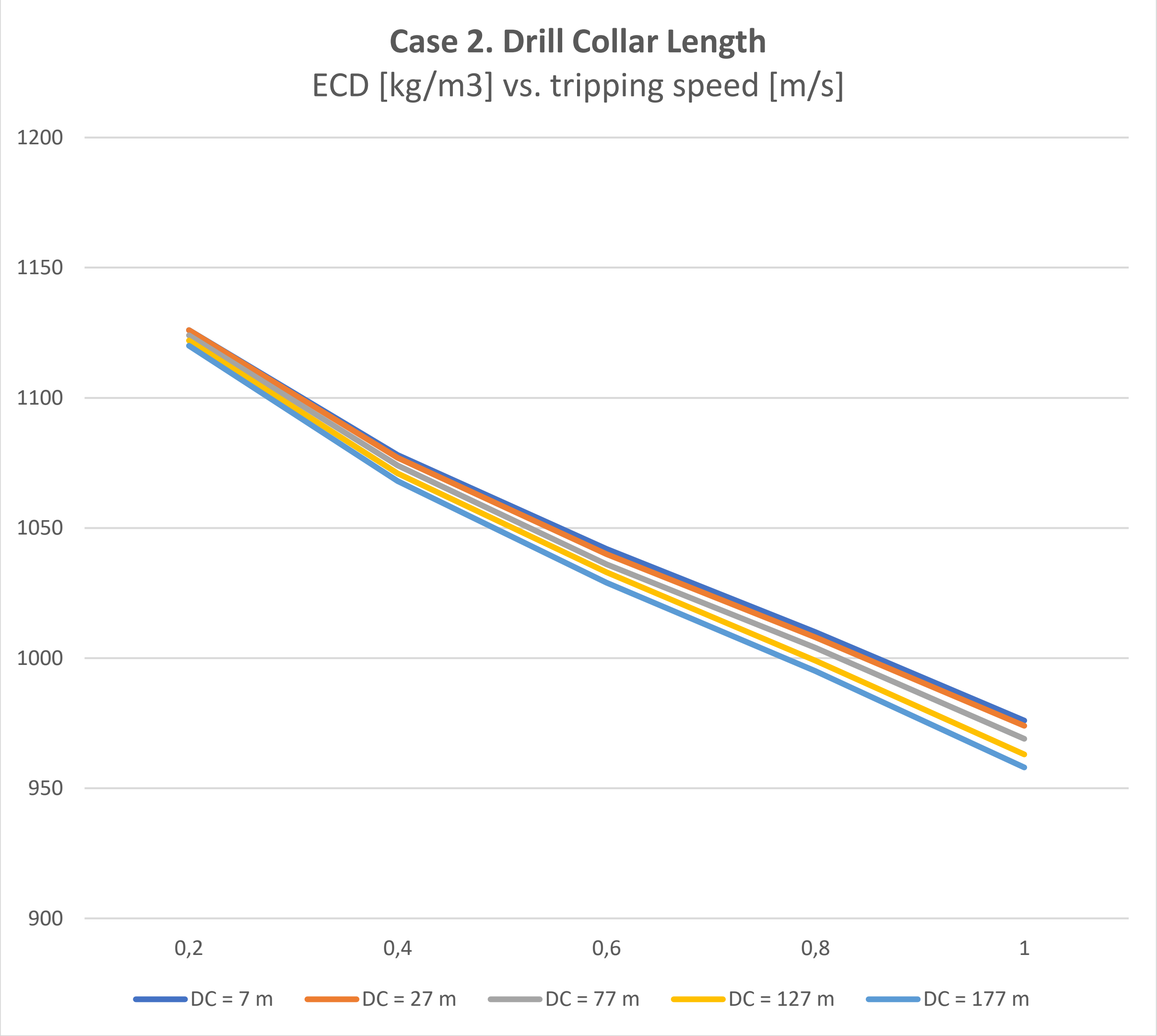


Figure 40: Case 2. Drill Collar Length sensitivity

The alterations made in the drill collar length is quite severe. There is a small difference in ECD at tripping speed 0.4 m/s of 3 kg/m^3 by adding 50 meters of drill collar. Compared to case 1, for the same tripping speed, the difference in ECD was 3 kg/m^3 by adding 77.5 meter to the MWD. The length of the BHA seems to matter slightly more for the surge and swab effects in case 2, but the effect is minor.

Diameter

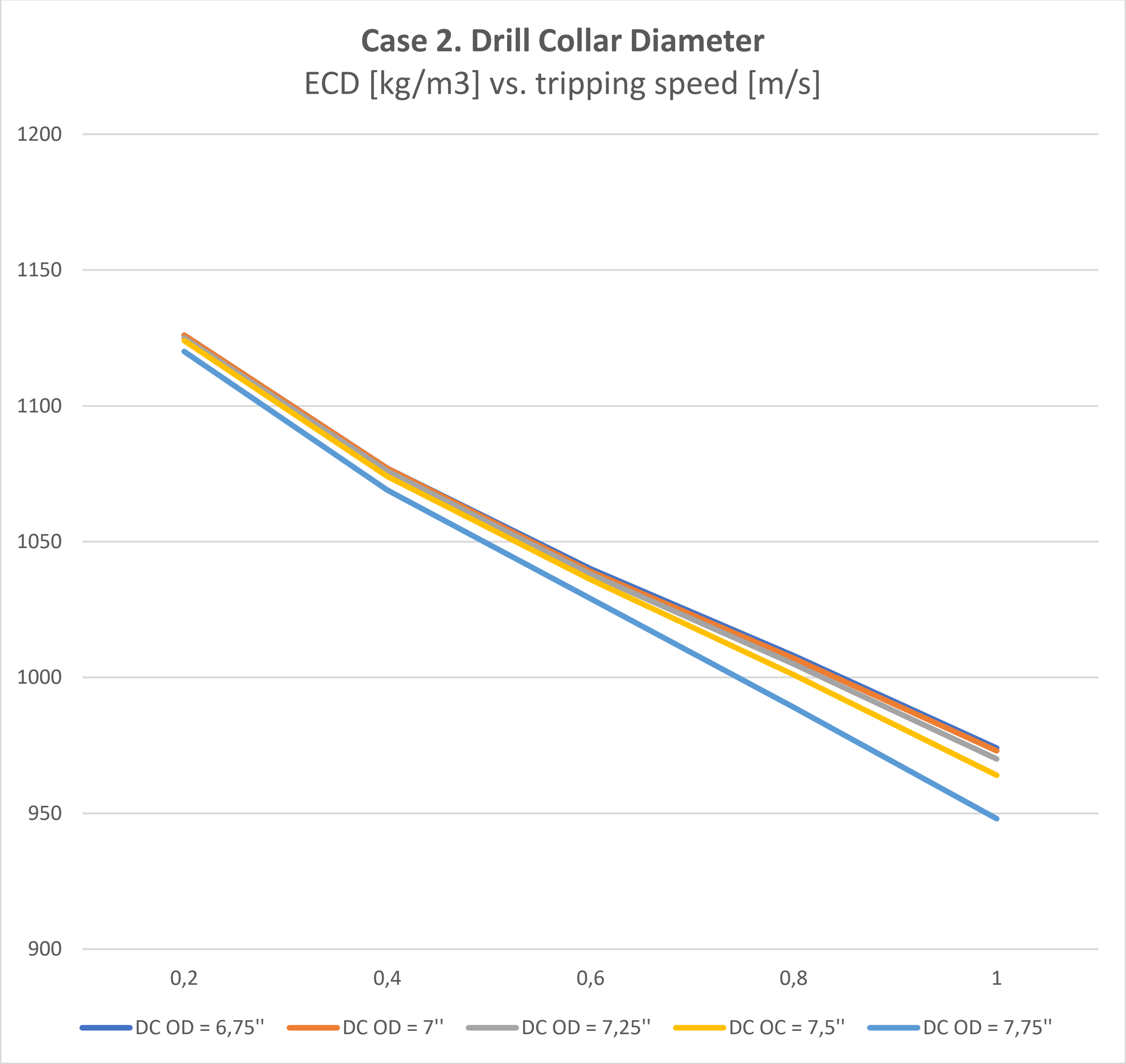


Figure 41: Case 2. Drill Collar Diameter sensitivity

One inch increase in the drill collar diameter changes the ECD with 8 kg/m^3 for tripping speed 0.4 m/s. The changes in the drill collar diameter in this analysis is smaller than for the MWD in case 1, because small changes made more difference in ECD in case 2. For comparison, by increasing both diameters 2 inches, the change in ECD for 0.4 m/s is 3 kg/m^3 for case 1 and 126 kg/m^3 for case 2. This can be explained by the size of the bit and open hole, where a 2 inches increase for case 1 makes the MWD 0.75 inch smaller than the bit, while for case 2, the drill collar is then only 0.5 inch smaller than the bit. It is obvious that when the BHA tools diameter is close to the bit diameter, the ECD is heavily affected. The pressure loss over BHA seems to be of a significantly importance to provide good approximations of surge and swab pressures.

5.2.6 Annular Clearance

Also for case 2, two different scenarios are created to analyse the annular clearance impact on surge and swab. In scenario 1, the drill pipe diameter is altered, where the original diameter is 5 inches. In scenario 2, the open hole and bit diameter is changed, originally being set to 8,5 inch.

Scenario 1

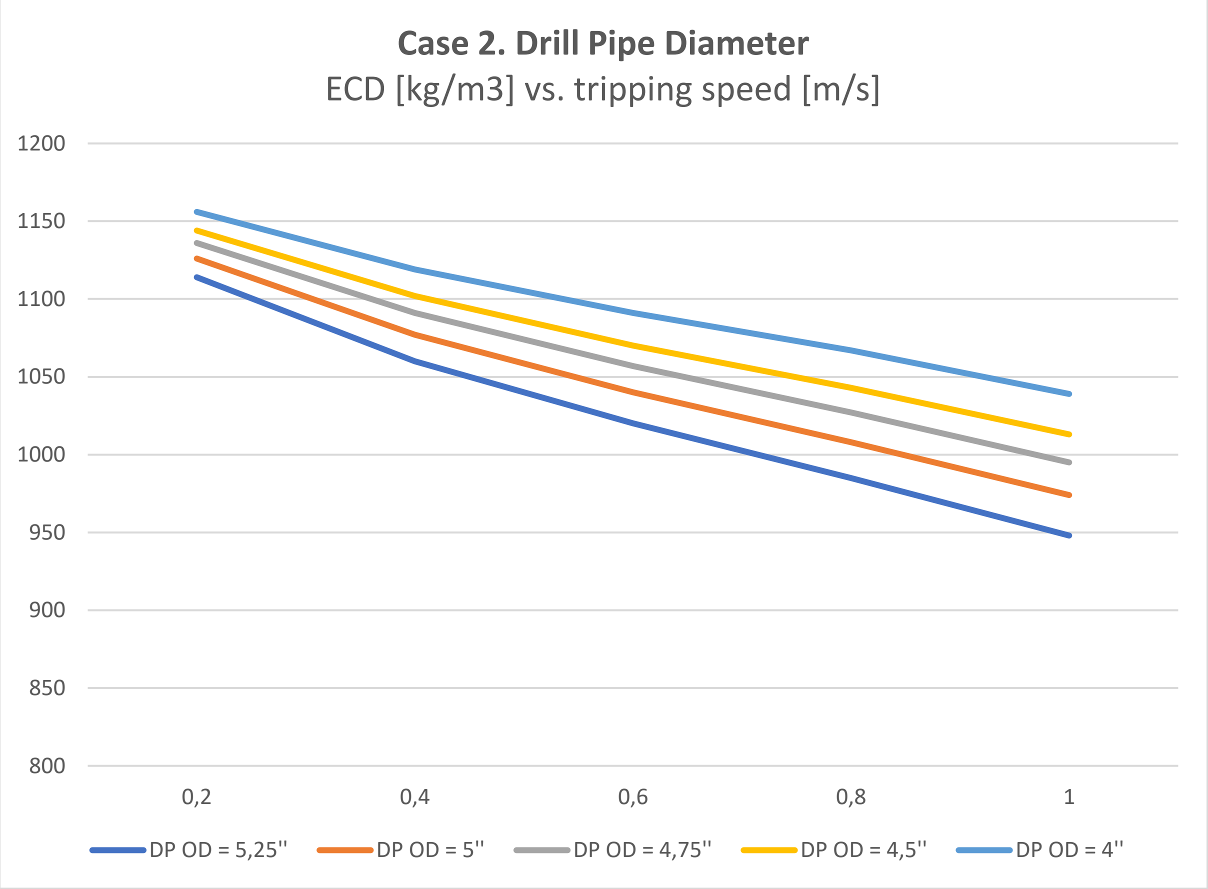


Figure 42: Case 2. Drill Pipe Diameter sensitivity

The enhanced annular clearance by increasing the drill pipe outer diameter affect the ECD considerably in a positive matter. For 0.4 m/s, one inch decrease of the drill pipe diameter increases the value of ECD with 42 kg/m^3.

Scenario 2

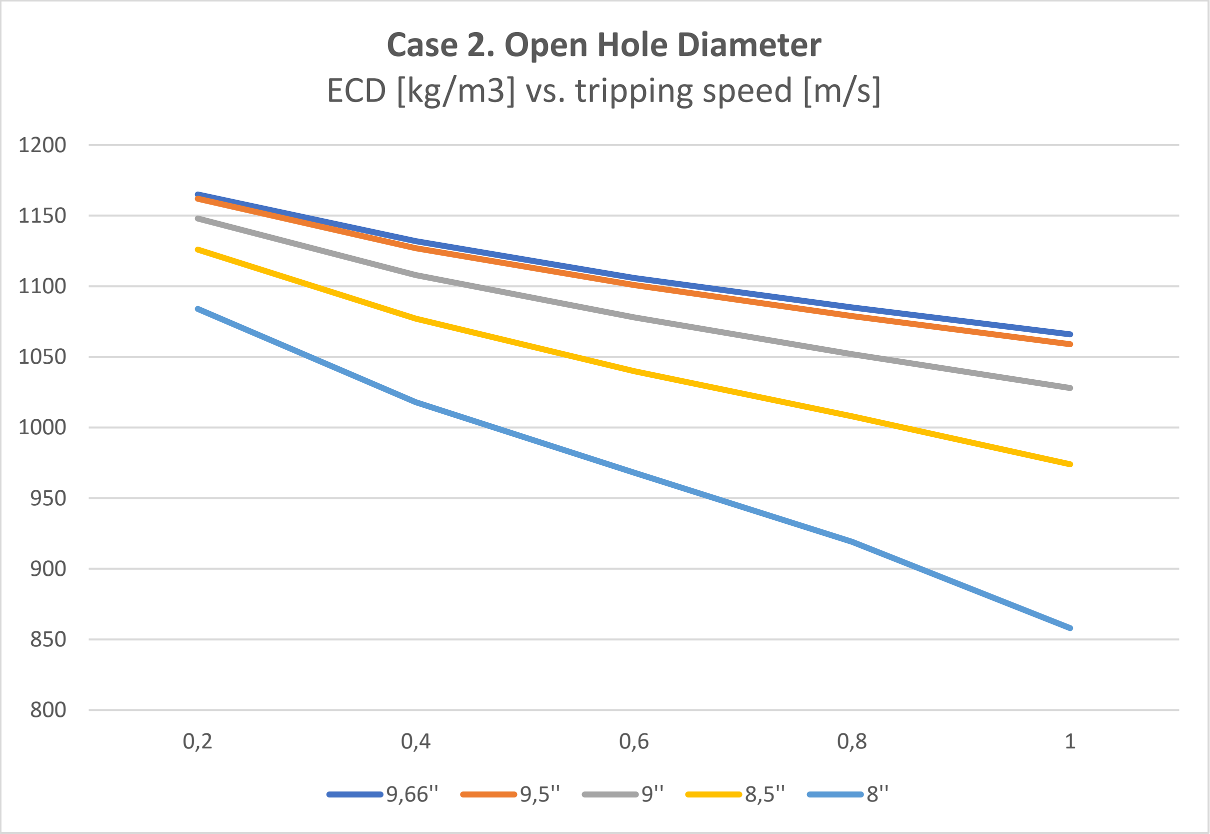


Figure 43: Case 2. Open Hole Diameter sensitivity

By increasing the open hole section with one inch, the difference in ECD for 0.4 m/s is 50 kg/m^3, notably higher than the one inch change of the drill pipe diameter. The overall ECD is more heavily affected by increasing the hole diameter than for reducing the drill pipe size.

5.3 Drill Bit Dimensions

The pressure loss over the drill bit is known to be of such a magnitude that it impacts the surge and swab effects greatly. The dimensions of the drill bit are complex, and calculations of the pressure loss over the complex area is difficult to execute. The numbers, design and material of the cones, together with the size and numbers of the nozzles, is known to be of some importance to the surge and swab effects. Changing the type of bit used, to other types in the WellPlan library, there was no change in the ECD. Also changing the nozzles and number of cones did not change the estimations of ECD. One can assume the dimension complexity is not taken into consideration in the WellPlan calculations on ECD, making the estimations of pressure loss over the drill bit uncertain for this sensitivity study.

5.4 Summarization of the sensitivity results

To estimate the impact each parameter has on surge and swab, a factor of impact is calculated using the following formula for the 0.4 m/s tripping speed results:

$$\text{Factor of impact on ECD} = \frac{\Delta \mathrm{ECD}/\mathrm{ECD}}{\Delta\ \text{of parameter analyzed}/\text{original value of parameter analyzed}} \tag{18}$$

	Case 1	Case 2
Density Bingham	0,0000	0,0000
Density Power Law	0,0000	0,0000
Density Herschel-Bulkley	0,0000	0,0000
Density average	0,0000	0,0000
Plastic Viscosity Bingham	0,0021	0,0104
n Power Law	0,0037	0,0446
K Power Law	0,0064	0,0738
n Herschel-Bulkley	0,0037	0,0564
K Herschel-Bulkley	0,0086	0,0732
Plastic Viscosity average	0,0049	0,0517
Bingham Yield Point	0,0187	0,0104
BHA length	0,0001	0,0013
BHA diameter	0,0202	0,0432
Drill pipe diameter	0,0125	0,1680
Open hole diameter	0,0261	0,3800

Figure 44: Calculated Factor of impact on ECD

The factor of impact on ECD from density is 0. As stated earlier this chapter, the ECD changes with the same amount as the change in density, which indicates no impact when the tripping speed increases. Open hole diameter has the largest factor of impact on ECD for both cases. For density and plastic viscosity, the average value of the factor of impact on ECD is calculated to provide a general factor of impact for the parameters with varying results dependent on fluid behaviour model.

6. Discussion

The objective of this sensitivity study was to use WellPlan to estimate the importance of different parameters on surge and swab effects when tripping in and out of a well. The results in chapter 5 provides a study of the accuracy of the mathematical models used today for estimating the drilling fluid behaviour, the effect of changing the fluid properties, and the importance of downhole dimensions.

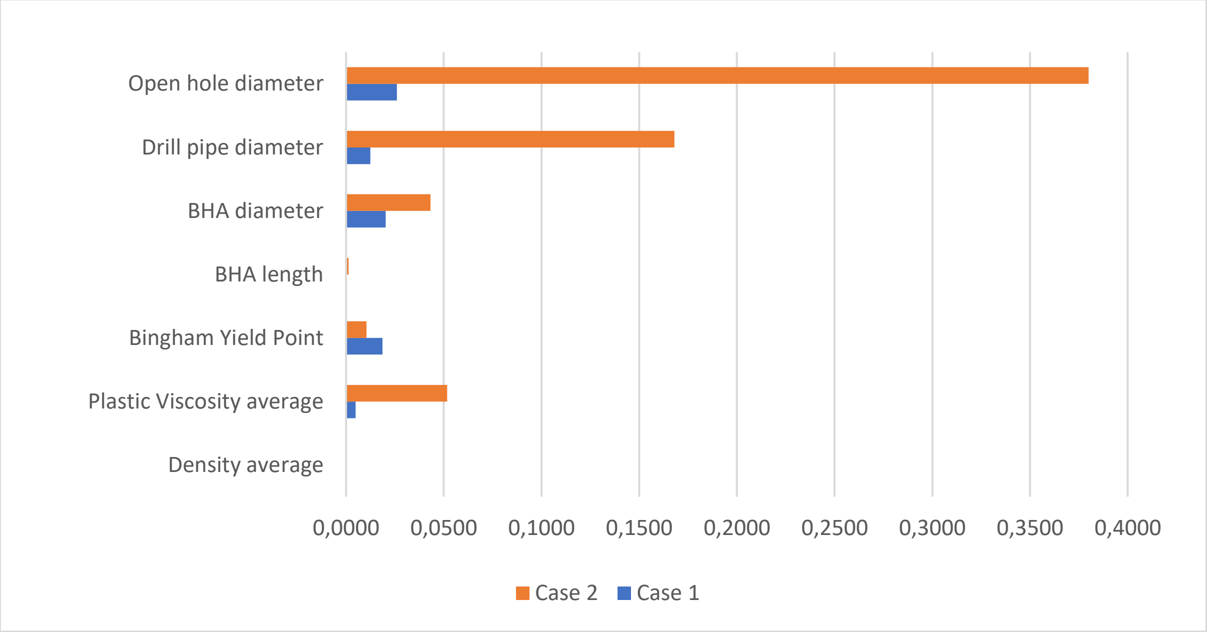


Figure 45: Sensitivity Analysis

This graph shows the factor of impact on ECD for each parameter. It is clear from this results that surge and swab pressures are heavily dependent on the annular clearance of the well compared to the other parameters tested. The size of the open hole and drill bit, together with the drill pipe diameter is the most significant parameter to consider when estimating surge and swab from this analysis. The different parameters impact on ECD is generally significantly higher for case 2 than for case 1, which testifies to the importance of downhole conditions and the complexity of the well when estimating surge and swab pressures. Annular eccentricity is not taken into account, which may reduce the ECD changes for case 2.

The results of the sensitivity analysis are that the parameters impact on surge and swab pressures is as follows, from most to least impact, for case 1:

1. Open hole and bit diameter
2. MWD diameter
3. Yield Point
4. Drill pipe diameter
5. Plastic Viscosity
6. MWD length
7. Density

And for case 2, it follows:

1. Open hole and bit diameter
2. Drill pipe diameter
3. Plastic viscosity
4. Drill collar diameter
5. Yield point
6. Drill collar length
7. Density

Quality of the program

WellPlan is commonly used in the petroleum industry today, providing the best and most advanced calculations and simulations of the entire drilling process. The results for ECD estimations are very acceptable, but could be more accurate if the bit dimensions would be considered in the ECD calculations. Also it would be beneficial if the output data could be provided with more digits.

Quality of the data

The data for the case investigated are satisfying for this sensitivity study, and are real data from a real well. There is also provided real time drilling data for a tripping out operation. Thus, the case data is somewhat simplified, especially when it comes to the BHA. Unfortunately, this affects the results significantly.

Future Work

Knowing that the BHA is of such importance for pressure loss, a sensitivity study containing all the components and dimensions of a real BHA would be of interest for future work. The impact of potential annular eccentricity and the temperature effects may also be of importance to surge and swab, and could be investigated further.

7. Conclusion

Testing the different parameters effect on ECD when tripping out with velocities between 0.2 m/s and 1 m/s, the conclusions about their sensitivity regarding surge and swab effects are as follows:

- The Herschel-Bulkley fluid behaviour model provides the most accurate estimations of drilling fluid behaviour out of the existing models.
- The density of the drilling mud will not affect the ECD in a greater amount than the density added to the mud or the density reduction of the mud, independent of the tripping speed.
- Both the yield point and the plastic viscosity of the fluid has small effects on ECD, and needs to be considered in the estimations.
- The detailed components and dimensions of the BHA cannot be neglected or simplified to obtain accurate values for ECD.
- The BHA diameter seems to be more important than the BHA length for surge and swab.
- The annular clearance is the most important factor for surge and swab pressures of the parameters analysed in this sensitivity study.
- The size of the open hole and bit is more important for annular clearance than the drill pipe size.
- The majority of the pressure changes occurs around the drill bit, and the surge and swab pressures depend heavily on the diameter of the bit and BHA.

Nomenclature

A	Flow area
a	Constant
D	Diameter
f	Friction factor
g	Gravitation constant
K	Consistency factor
Kc	Clinging constant
L	Length
N	Flow behaviour index
P	Pressure
Q	Flow rate
Re	Reynolds number
v	Velocity
z	Section length
Δ	Difference
γ	Shear rate
μ	Viscosity
θ	Dial read from viscometer
ρ	Density
τ	Shear stress

Abbreviations

BHA	Bottom Hole Assembly
ECD	Equivalent Circulating Density
MD	Measured Depth
MWD	Measurement While Drilling
OBM	Oil-Based Mud
OD	Outer Diameter
PV	Plastic Viscosity
TVD	True Vertical Depth
WBM	Water-Based Mud
YP	Yield Point

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