MONTAN
UNIVERSITÄT
LEOBEN

Chair of Drilling and Completion Engineering

Master Thesis

Solids Induced Stuck Pipe Events - Development of Digital Best Practices for NPT Prevention

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Mai 2019

This thesis is dedicated to the best dad in the world, who enabled me all the things that make me to the person I am today.

Affidavit

I declare in lieu of oath that I wrote this thesis and performed the associated research myself using only literature cited in this volume.

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Abstract

Incorrect operational parameters, bad hole cleaning, unknown formation properties and suboptimal BHA design can lead to solids induced stuck pipe events. Stuck pipe due to pack-off does not occur suddenly, but is noticeable by typical symptoms like an increase in torque, drag and pump pressure. Recognising and adequately reacting to these signs can help to prevent the occurrence of this costly and time-consuming situation. In an attempt to avoid such problems during drilling, an interactive and realistic training case is developed on the state-of-the-art eDrilling AS simulator as part of this master thesis. It allows students and technical staff to train their skills on stuck pipe detection and mitigation. Supplementary to turning trainees into highly qualified personnel, the potential to reduce the non-productive time (NPT) during operations is one of the significant advantages of this digital training case for operators and service companies.

Through an extensive literature review the different mechanisms leading to solids induced pipe sticking, including its indications, measures to prevent their occurrence, and the best practices how to get free are found out. Together with the involvement of the experience of industry professionals, the best-practices for avoiding and getting out of this kind of drilling troubles are elaborated. Based on these procedures, a suitable scenario for the implementation of the training case is developed. Afterwards, the derived scenario is transformed into a JavaScript software code which is checked for its functionality on the eDrilling simulator. The completion of the code is followed by a workflow description on how to run through the developed scenario which leads to the ready-to-use training case.

The simulator itself is a multifunctional tool that does not only allow the integration of all parameters which are present during real drilling operations but also enables the graphical visualization of it. The numerous possibilities to extend the existing functions and the required knowledge on how to use the simulator complicate its utilisation. To avoid these difficulties the preparation of the input data, such as trajectory and BHA design, must be done properly and can be facilitated by the supportive application of a well design software. The workflow on how to implement scenarios facilitates the implementation of further cases into the simulator and thereby provides the opportunity to enlarge the training offer. Besides, the description of the solution of the developed training case serves the user to acquire the best-practice in such a sensitive situation.

As this is the first training case on the eDrilling simulator which interactively confronts the user with the issue of solids induced stuck pipe, it offers a unique solution for future education. Its launch supports the transformation of trainees into highly qualified staff and promotes the digitalisation attempt of the oil and gas industry by digitising the best-practice of solids induced stuck pipe events. Through the combination of scientific background and operational experience in a realistic hands-on drilling scenario the basis for the skilled employee of tomorrow is provided.

Zusammenfassung

Falsche Bohrparameter, ungünstige Bohrlochreinigung, unbekannte Untergrund=eigenschaften und suboptimales Design der Bohrgarnitur können zu bohrkleininduziertem Festwerden des Bohrstranges führen. Das Festwerden aufgrund von Bohrklein tritt nicht plötzlich auf, sondern macht sich zuerst durch Symptome bemerkbar. Das Erkennen und richtige Reagieren auf diese Anzeichen kann dazu beitragen, das Erscheinen dieser kostenintensiven und zeitraubenden Situation zu vermeiden. Um das Auftreten dieses Problems während des Bohrens zu verhindern, wurde im Rahmen dieser Masterarbeit ein interaktiver und realistischer Trainingsfall auf dem hochmodernen Bohrsimulator des Unternehmens eDrilling AS entwickelt. Dieser ermöglicht es, die Kompetenzen von Studenten und Fachpersonal im Erkennen und richtigen Reagieren auf Anzeichen eines bohrkleininduzierten Festwerden des Bohrstranges auszubauen. Darüber hinaus zählt auch das Potenzial zur Reduzierung der „Non-Productive Time“ (NPT) während des Bohrbetriebs zu den größten Vorteilen dieses digitalen Trainingsfalls.

Durch eine umfassende Literaturrecherche wurden die Mechanismen, die zum Auftreten von bohrkleinbedingtem Festwerden führen können, einschließlich der Vorkehrungen um dessen Eintreffen abzuwenden und den besten Praktiken wie ein festgewordener Bohrstrang befreit werden kann, zusammengetragen. Unter der Einbeziehung der Erfahrung von Fachleuten wurden anschließend die in der betrieblichen Praxis entwickelten besten Lösungen für die Vermeidung und das Lösen bohrkleinbedingt festgewordener Bohrstränge erarbeitet. Darauf basierend wurde ein geeignetes Szenario für die Implementierung des Schulungsfalls entwickelt. Darauffolgend wurde der abgeleitete Anwendungsfall in einen JavaScript-Softwarecode umgewandelt, dessen Funktionalität laufend auf dem eDrilling-Simulator überprüft wurde. Der Fertigstellung des Codes folgte letztlich die Beschreibung, in Form eines Workflows, über den Ablauf des fertigen Trainingsszenarios.

Der Simulator ist ein multifunktionelles System, das nicht nur die Integration aller Bohrparameter, die auch bei realen Bohrungen vorhanden sind, ermöglicht, sondern auch eine visuelle Darstellung des Bohrbetriebs zulässt. Die vielfältigen Möglichkeiten die bereits vorhandenen Funktionen zu erweitern sowie die erforderlichen Kenntnisse zur Verwendung des Simulators erschweren dessen Handhabung. Um diese Schwierigkeiten zu vermeiden, muss die Aufbereitung der Eingabeparameter sehr sorgfältig durchgeführt werden. Dieser Prozess kann durch die unterstützende Anwendung von Bohrplanungsprogrammen erleichtert werden. Neben einem detaillierten Arbeitsablauf, welcher die Implementierung weiterer Szenarien in den Bohrsimulator vereinfacht, hat der Benutzer durch die Beschreibung der konzipierten Übungsaufgabe die Möglichkeit, sich den besten Lösungsansatz in solch einer sensiblen Situation anzueignen.

Da dies der erste Trainingsfall auf dem eDrilling-Simulators ist, der den Benutzer interaktiv mit diesem Bohrproblem konfrontiert, bietet er eine einzigartige Möglichkeit für die zukünftige Ausbildung. Seine Einführung unterstützt Auszubildende auf ihrem Weg zu hochqualifiziertem Personal. Durch die Kombination von wissenschaftlichem Hintergrund und betrieblicher Erfahrung in einem realistischen, vom Benutzer selbst beeinflussbaren Bohrszenario können die Kompetenzen des Facharbeiters von morgen auf ein neues Level gebracht werden.

Acknowledgements

I would like to thank the Department of Petroleum Engineering, especially the chair of Drilling and Completion Engineering and my mentor Dipl.-Ing. Anton Lettner, for giving me the possibility to write this master thesis.

Furthermore, I want to show my appreciation to OMV AG, in particular to Dipl.-Ing. Richard Kucs and Mr. Matthew Cullen for always supporting me.

Big thanks also go to my colleagues and friends, Alexander Karl, Julian Pflügl, Max Hädicke and Andreas Ortner who motivated and pushed me to give my best during my entire studies.

Contents

Chapter 1 Introduction

Incorrect operational parameters, bad hole cleaning, unknown formation properties, and suboptimal BHA design can lead to solids induced stuck pipe events. After the statements by Muqeem et al. (2012) stuck pipe accounts for about 25% of the non-productive time (NPT) during drilling operations and is one of the most critical problems in the oil and gas industry. Oketch (2014) reported that stuck pipe events are costing the drilling industry 200-500 million $ every year and are occurring in 15% of the wells. However, stuck pipe events do not only lead to NPT and loss of money but can also create severe safety issues in context with the wellbore and the people working on the rig site. As it is tried to free the stuck pipe, the sudden liberation can release high forces which consequently may damage the wellbore, equipment, downhole installations and injure human beings. According to Salminen et al. (2016), pack-off and bridging make out 65% of all stuck pipe causes and is, therefore, the most common reason for stuck pipe worldwide. It typically occurs when pulling out of the hole (POOH) or when the pipe has been motionless for some time with the pumps turned off. Just in a few cases, the drill string packs-off during running in hole (RIH). Solids induced stuck pipe events are likely to be the most severe type of stuck pipe as there is usually a lower chance of freeing than in the differential or wellbore geometry connected case of sticking. Consequently, more tools are lost and more sidetracks have to be drilled due to pack-offs. The probability of suffering a stuck pipe event even increases in smaller hole sections and horizontal wells as the removal of cuttings gets worse. The accumulation of drilled cuttings in the annular space caused by inadequate hole cleaning can result in a solids induced stuck pipe event. In directional-well drilling, a stationary cuttings bed may form on the low side of the borehole. When tripping out, this condition is very likely to cause solids induced pipe sticking. Since the industry is moving towards the drilling of longer horizontal sections, to improve the reservoir contact area and thereby the productivity of the reservoir, the problem becomes more important. Therefore, the personnel needs to receive proper training to be able to identify this problem in the early stage and to set the right measures to avoid its further growth (Mitchell 2014; Cullen and Kucs 2018).

The goal of this thesis is to improve the drilling efficiency, reduce solids induced stuck related NPT using state-of-the-art drilling simulator in combination with tailor-made training scenarios for engineers and operational personnel. The best practice according to literature and the experience from experts in this field will be used to develop a handbook to avoid solids induced stuck pipe events. This best practice and a realistic solids induced stuck pipe scenario will be implemented into the drilling simulator at the Montanuniversität Leoben. Thereby, students and professionals can train their skills on stuck pipe detection and mitigation.

Chapter 2 Theory and types of solids induced stuck pipe events

In history, stuck pipe events were categorized either into mechanically stuck or differentially stuck. State-of-the-art thinking now splits mechanical sticking into two distinct groups, pack-off and bridging, and wellbore geometry associated sticking. This differentiation is made because the mechanisms which stick the pipe in pack-off and geometry linked incidents are evidently not the same (Mitchell 2014). Solids induced stuck pipe events[1] are caused by deposition of formation fragments and particles around the drill string and cost the oil and gas industry not only a lot of time and money but also much patience. Pieces of rock accumulate over the BHA and other sections of the drill string and thereby increase the force necessary to move it. According to the definition of Schlumberger and Anadrill (1997), the string is stuck when the force required to move exceeds the capability of the rig or the tensile strength of the drill pipe. Generally, pack-off and bridge sticking can happen during any kind of operation, but the majority occurs when the drill string is POOH.

To understand the different sticking mechanisms, shown in Figure 1, and their influencing factors is of great importance to set the right actions for optimal prevention. In this Chapter, the various mechanisms leading to solids induced pipe sticking are discussed, including measures to prevent their occurrence, indications and the best practices how to get free.

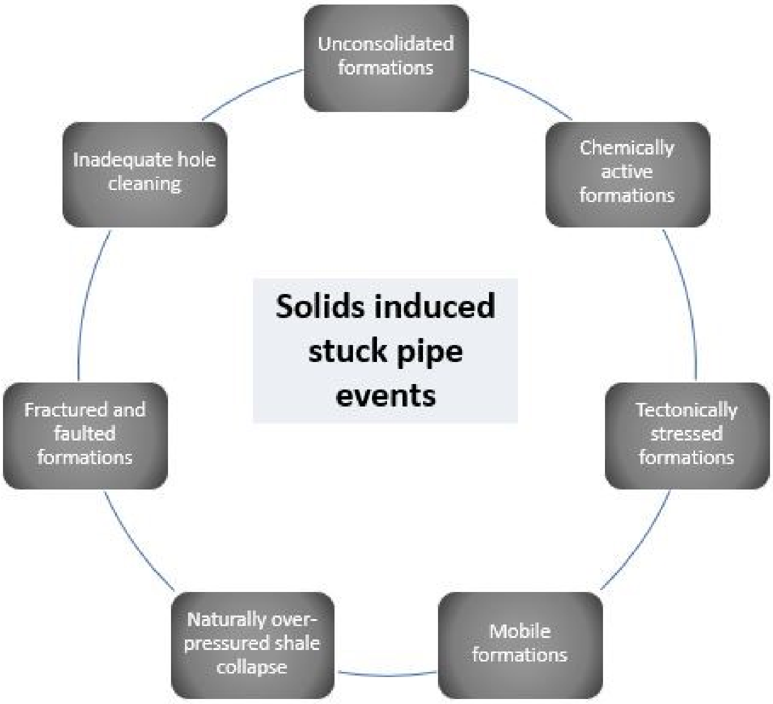

Figure 1: Stuck pipe mechanisms

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[1] Also know under the term solids induced pipe pack-off

2.1 Unconsolidated formations

Office of Water Programs (2017) describes unconsolidated formations as loosely arranged or unstratified whose particles are not cemented together. During drilling, they can collapse as shown in Figure 2. The un-bonded formation such as sand and gravel cannot be supported by the hydrostatic column of mud resulting in large and cavernous washouts. The drilling fluid basically flows into the formation and causes it to fall into the wellbore where it pack-offs the drill string. This mechanism can be often observed when drilling shallow hole sections. The just explained effect can be compared to digging a hole in the sand on the beach. The created hole will collapse because the friction between the grains is not high enough for the walls to stand vertically and the material will accumulate at the bottom (Bowes and Procter 1997).

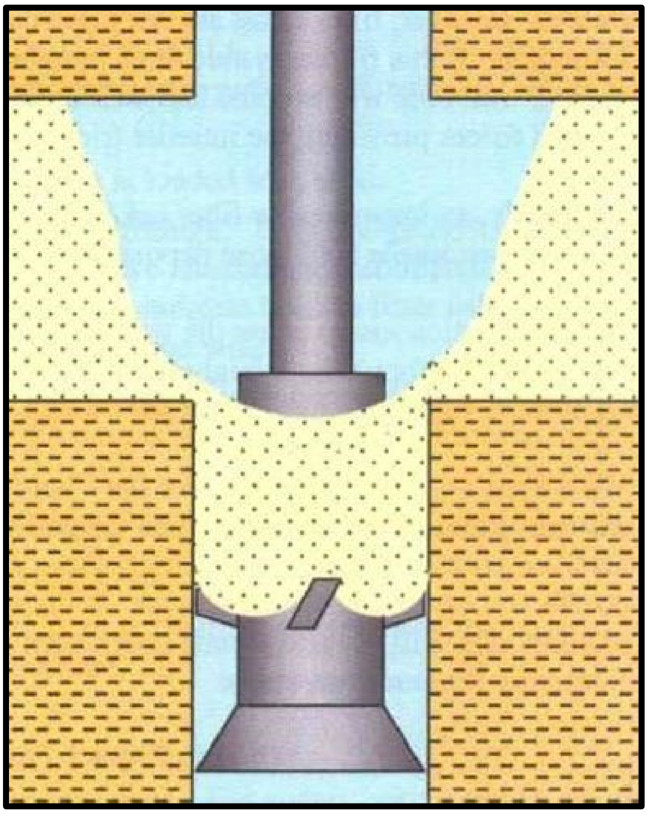

Figure 2: Unconsolidated formation (Mitchell 2014)

2.1.1 Indications

A stuck pipe as a consequence of unconsolidated formation falling into the wellbore can happen either while tripping or drilling. According to Schlumberger and Anadrill (1997) and Mitchell (2014), the subsequent signs are indicative when this problem is coming up:

- Large amounts of sand on the shale shakers; It is a sign for encountering an unconsolidated formation when more material is being removed than was drilled
- Increase of the mud weight due to the large amounts of solids

- Backflow on connections as the density in the annulus is higher, because of the unconsolidated sand, than in the drill pipe[2]
- Torque, drag and pressure peaks if the sand is flowing hard
- Torque and drag drastically decrease once circulation is established after a connection
- Increase in standpipe pressure appears when the annulus is full of sand
- Lost circulation: As unconsolidated formations are typically very permeable, continuous fluid loss is a warning sign for encountering problematic zones
- Overpulls on connections

2.1.2 Preventive measures

To avoid the problem of stuck pipe due to an unconsolidated formation, an adequate filter cake is requisite as it helps to stabilize the drilled rock. As long as this filter cake exists and sufficient overpressure can be applied against it, the wellbore will be stable. Elmgerbi and Prohaska (2019) state that this can be achieved by adding filtrate reducers or lost circulation material such as bentonite clays, lignite or carboxymethylcellulose to the mud. This prevents the mud from entering the formation and carrying the rock particles into the wellbore (Bowes and Procter 1997).

Related to explanations of Bowes and Procter (1997), the following actions counteract the occurrence of the described problem:

- The first action, if pump pressure is increasing, is to pick off bottom and circulate
- Excessive circulation with the BHA in the interval of unconsolidated formations should be avoided to reduce erosion.
- Pumping a gel pill before POOH; high viscosity pill will support the cuttings and improve cleaning
- Selection of a low tripping speed when the BHA encounters unconsolidated formations to deter damage
- Increasing and decreasing the pump rate in small steps to counteract pressure surges being applied to unconsolidated formations
- Reduction of the rate of penetration (ROP) in suspected zones to allow the filter cake to build up
- Monitoring the shaker screens, desilter and desander for overloading
- Installation of shock-subs in the drill string to mitigate vibrations as they can lower the friction between the grains and lead to instability
- *The sooner casing can be set the better* (Mitchell 2014).
- Addition of lost circulation material and fluid loss agents to the mud
- Mitchell (2014) recommends never leaving the bit on bottom when the pumps are turned off but keeping the pipe in motion

When wellbores are constructed in permafrost regions, unconsolidated formations are cemented with ice and give the impression of being consolidated. Due to heat during drilling (mud, friction) the frozen formation will thaw and become unconsolidated. To limit the degree of thawing mud coolers are applied (Mitchell 2014).

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[2] U-tube effect

In the North Sea, the subsequent method is applied when struggling with unconsolidated formations during the well construction stage: After drilling 10 meters, the string is pulled up to the top of the section and waited until 10 minutes have passed. When lowering the string and the solids fill on bottom is large, this procedure is carried out again every 10 meters. It might be unmanageable to avoid the collapse of the hole, and therefore, the hole is left to itself to stabilize while the BHA is up, out of the critical zone (Bowes and Procter 1997).

2.1.3 Freeing

When noticing first indications of an upcoming stuck pipe event due to an unconsolidated formation, the pump strokes have to be reduced by half as this will lower the pressure trapped in case the hole packs-off. Too much pressure applied to the pack-off will worsen the situation. In case that this approach cleans up the hole, the flow rate can be returned in small steps to its initial value (Bowes and Procter 1997).

If the approach mentioned above cannot improve the situation and the string packs off, the pumps must be stopped instantly, and the procedure presented by Bowes and Procter (1997) followed:

- The standpipe pressure has to be bled off at a controlled rate to approximately 500psi so that no solids can enter the drill string. The left pressure of 500psi below the pack-off functions as an indicator. If the pressure bleeds off, the driller knows that the situation is getting better. While keeping the standpipe pressure at a maximum of 500psi and the drill string hanging at free rotating weight, the maximum permissible torque should be applied. Moving the string up or down is not recommended at this stage.
- In case that the pressure starts to bleed off or partial circulation is established, increasing the pump rate slowly to maintain a maximum of 500psi standpipe pressure is proposed.
- If circulation cannot be regained, working the pipe between free up and free down weight is recommended. The application of torque during downward movement helps to un-bridge and break free from a pack-off. However, excessive pulls are not suggested as it would aggravate the situation.
- The application of jars is not proposed at this stage.
- If circulation could not be re-established up to this point, starting to increase the standpipe pressure in steps up to 1500 psi and continuing to move the pipe up and down while applying torque is advised.
- In case circulation is restored, but the pipe is still stuck, jarring operations in the opposite direction of last pipe movement are recommended. If the pipe cannot be freed downwards, it is possible to jar up through the sand.
- According to Mitchell (2014), the application of low-frequency tools helps to fluidize the sand.
- When the drill string gets free, rotating and hole cleaning before continuing the operation is necessary.

It must be kept in mind that if the pipe gets stuck during drilling shallow formations, the proposed pressures might not be achievable.

2.2 Chemically active formations

Chemically active formations are formations that contain high amounts of bentonitic and montmorillonite minerals. These clay minerals are naturally occurring in shales, have a great capacity to absorb water and start to hydrate when getting in contact with mud filtrate. During drilling, the calcium-ions in the formation will exchange with the sodium-ions from the mud. As sodium has the ability to absorb more water than calcium, the clay in the shale formation will start to swell. Once the shales are hydrated, they start to expand and thereby reduce the wellbore diameter or drop into the borehole (see Figure 3). In that way, the bit has the tendency to "ball-up" during drilling and the bottom hole assembly (BHA) can get stuck in swelled sections of the wellbore (Netwas Group Oil 2019).

Mitchell (2014) states that if shale is encountered during drilling, wellbore instability should be expected. This rock type can weaken over time which means that it can be stable while it is drilled but get instable due to mud filtration after a while.

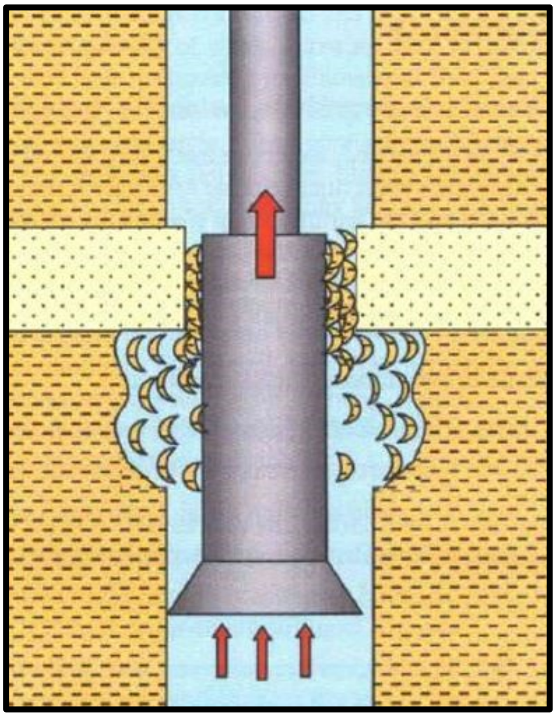

Figure 3: Reactive formation (Mitchell 2014)

2.2.1 Indications

According to Bowes and Procter (1997) and Mitchell (2014), an approaching stuck pipe event due to reactive formations can be recognized by the signals mentioned below. For better overview they are grouped into three categories:

Connection:

- Increase in torque and drag; Drag is very smooth as the BHA is pulled into a tight spot
- Overpull when picking up off the slips

- Pressure peak when circulation is started after the pumps were switched off due to higher gel strength and plastic viscosity (PV) of the mud

Tripping:

- Smooth but increasing torque and drag
- Loss of mud while tripping in
- Increase of filter cake thickness
- Increase or fluctuations in pump pressure
- Circulation is impossible or highly restricted

Drilling:

- Hydrated, paste-like cavings or large clumps of hydrated shale coming out of the hole
- Low ROP
- Need to increase WOB to maintain the ROP
- Shakers screens get plugged by clay balls or sticky cuttings
- Volume percentage of low gravity solids (LGS) increases (clays, sands, etc.) which raises the mud weight
- Torque and drag trends are increasing and smooth due to swelling of the formation; no fluctuations in torque and drag like when hole cleaning or cavings problems are faced
- Funnel viscosity, PV and YP increase
- Cation exchange capacity and its measure, the MBT value, increase
- BHA is packed-off with reactive clay during inspection[3]
- Drilling rate is reduced as less weight is transferred to the bit
- If pump pressure is building exponentially, it is a sign for swelling clays

2.2.2 Preventive Measures

The utilization of an inhibited mud system can mitigate this problem. Various salts (potassium, sodium, calcium, etc.) as additives will prevent the hydration of shales as they reduce the reaction rate between the mud and the formation. If the mud is saltier than the formation water, sodium from the formation will flow into the mud due to osmosis pressure and the fact, that flow always takes place from low to high salinity (Bowes and Procter 1997).

The potassium concentration in the mud affects the displacement probability. The potassium-ions in the mud will exchange with the calcium-ions in the formation. As potassium-ions combine low hydration energy with high bonding energy, dehydration of formation clay will take place. The formation clay platelets are pulled closer together, and the water is forced out. The stabilization of shale formations can be achieved by the addition of potassium chloride, potassium acetate, potassium carbonate, potassium hydroxide to the mud (Elmgerbi and Prohaska 2019).

Monitoring mud properties is the key to spot this problem. Drilling through shale formations will increase the calcium-ion concentration in the mud. As a consequence,

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[3] Bit balling

the cation exchange capacity will increase. With a methylene blue test (MBT), the amount of reactive clay-like minerals can be determined. A higher MBT value obtained by this test indicates a higher number of reactive clay (Elmgerbi and Prohaska 2019).

The execution of regular wiper trips or reaming trips, based on exposure time or warning signs of reactive shales, can help if shales begin to swell. Additionally, adequate hole cleaning to remove excess formation should be ensured (Schlumberger and Anadrill 1997).

Besides the already mentioned measures, Cullen (2019) recommends the following actions:

- Avoid long periods without circulation
- Minimize open hole time
- Be ready to ream during tripping
- Maximize flow rates
- Optimize bit selection: high open face area, small cuttings
- Usage of oil-based mud instead of water-based mud, because oil will not react with shale. However, this should be the last option as it is the most expensive one.

Magarini and Monaci (1999) propose to:

- Lower the pH-value of the mud to 8,5
- Use the minimum tolerable number of stabilizers
- Reduce rotary speed, if feasible, to 80rpm or less

2.2.3 Freeing

In case the drill string gets stuck due to reactive formations, Mitchell (2014) recommends the following procedure:

- Bleeding off any trapped pressure is the first step in any kind of pack-off. Otherwise, the piston effect will reduce the amount of applied downward force.
- Afterwards, the application of 200 to 500psi is proposed, then torqueing and slumping[4] the pipe to try to re-establish circulation. The application of torque assists in re-establishing circulation and pipe movement.
- As the majority of pack-offs occurs when moving the drill string out of the hole, it should be tried to work the string downwards, in the opposite direction of the last movement. Additionally, the cavings are moving downwards and would be pressed together during upward movement which would cause high wedging forces. Therefore, the most effective direction to move is downwards. Though in directional wells it can also happen that pack-off happens during RIH. In this case, the string should be moved up, not down.
- As torsional and tensile stresses are additive, jarring upwards during torque application is not recommended. Jarring down while applying torque is acceptable because torsional stress and compressive stress are not additive.

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[4] Sudden release of HL; the pipe kind of falls down

- Once circulation is re-established, it is essential to clean the wellbore before any further operation.
- Therefore, pumping a high viscosity pill in vertical and slightly deviated wells to clean the wellbore is recommended; In directional wells, it is advised to start with circulating low viscosity pills followed by more viscous ones.
- Adelung et al. (1991) advise that rotation may help to get rid of the pack-off material. Additionally, it may be supportive to raise the mud density if possible.
- When the string is released, POOH slowly to avoid swabbing

2.3 Tectonically stressed formations

Tectonic stresses form due to the movement of the earth's crust. As a consequence, the formations in these areas are compressed or pulled apart. If a wellbore is drilled, the hole collapses and caves in easily as the formation is buckled due to the force of the moving tectonic plates. As the fracture gradient is lower than the mud weight needed to stabilize the formation, it is very difficult to avoid breakdown of the wellbore. This phenomenon is mostly observed in mountain regions. For better visualization of this mechanism, Figure 4 is shown (Bowes and Procter 1997).

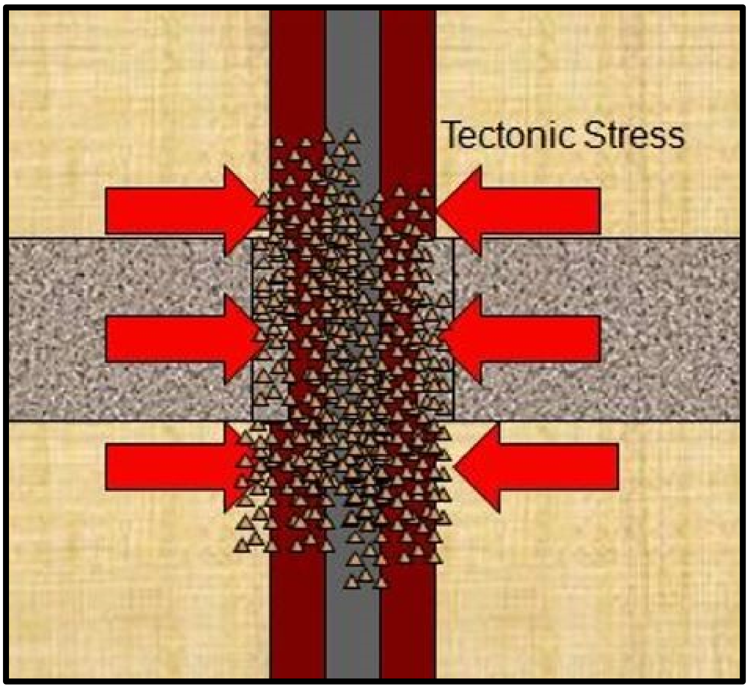

Figure 4: Tectonically stressed formations (Drilling Formulas 2012)

2.3.1 Indications

Bowes and Procter (1997) and Mitchell (2014) state, that recognizable symptoms of this sticking mechanism are:

- Overpull after connections as cavings have settled over the BHA as the pumps were turned off
- Torque and drag trends are increasing and erratic during drilling

- Pressure peak when circulation is started; Cavings obstruct flow when the pumps are switched on again
- Splintery cavings on the shale shakers, comparable to those created by over-pressured shale
- Increase in volume of returns relative to the hole volume drilled at the shakers
- Excessive and erratic drag during tripping
- Fluctuating torque, drag and pump pressure when reaming
- In case the drill string gets stuck, circulation is restricted or completely cut off

2.3.2 Preventive Measures

The actions proposed by Bowes and Procter (1997) to avoid the occurrence of a stuck pipe due to this phenomenon are the following:

- Sensitive formations have to be cased off as fast as possible
- Mud weight must be maintained within the determined mud weight window
- Selection of smaller hole sizes in problematic formations when possible, as this facilitates hole cleaning
- It must be ensured that the circulation system can manage the additional volume of cavings
- Selection of the most favorable inclination and azimuth by using offset data as these are key elements to lower the extent of the problem

2.3.3 Freeing

If the pipe gets stuck due to tectonically stressed formations, the problem arises as a hole cleaning difficulty. Therefore, the same steps should be performed as when getting stuck because of unconsolidated formations. The recommended actions are given at 2.1.3.

2.4 Mobile formations

This stuck pipe mechanism commonly occurs when salt formations are encountered during drilling. The mobile formation is compressed due to overburden weight and thereby, pushed into the wellbore. As these formations are characterized by their plastic behavior, the overburden stress causes them to expand laterally reducing the diameter of the wellbore (see Figure 5). Consequently, the running of BHA's, casing and logging tools is restricted. Mitchell (2014) states that only little difficulties arise during drilling these formations, but when the pipe is POOH the stabilizers or BHA can easily become wedged in the diameter-reduced section of the wellbore. In lots of cases, the deformation occurs since the mud weight is not sufficient to counteract the squeezing of the mobile formation into the wellbore. In addition, high tectonic stress and elevated temperature will support creeping and thick salt layers are more likely to move than thin ones (Bowes and Procter 1997).

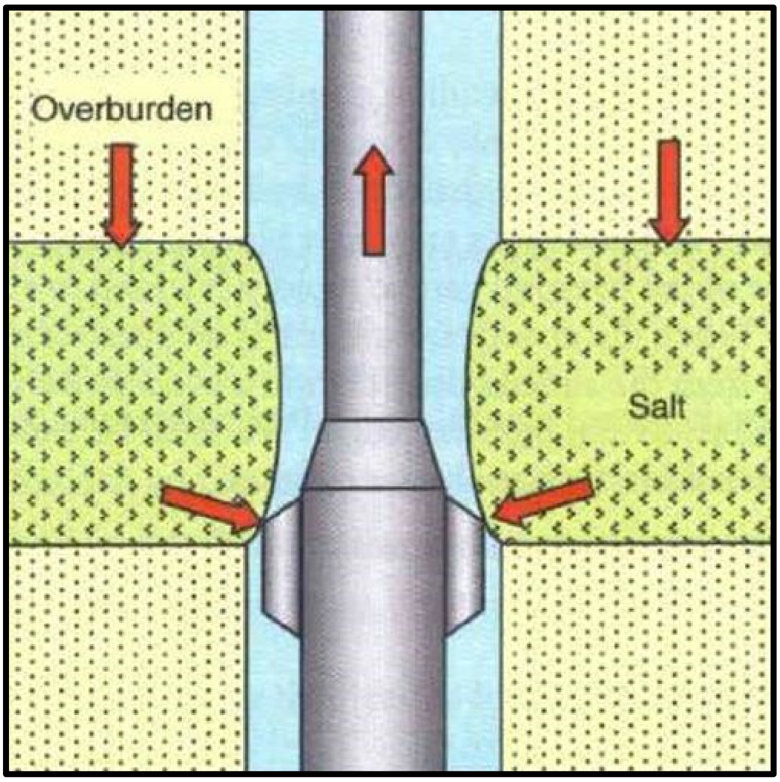

Figure 5: Mobile formation (Mitchell 2014)

2.4.1 Indications

The drill pipe can get stuck due to mobile formations during drilling or tripping operations. According to Bowes and Procter (1997), this type of stuck pipe can be identified by:

- High torque and drag while reaming or tripping due to reduced wellbore diameter
- Presence of salt or coal on the shaker screens
- A lack of cuttings, as WBM can completely dissolve the drilled salt cuttings
- High ROP and low vibrations are common when drilling thick salt layers
- Overpull when POOH
- Drill string weight decreases when RIH
- Restricted or reduced circulation at the depth of mobile formations
- High concentration of chlorides in the mud
- Mud resistivity decreases (Schlumberger and Anadrill 1997)
- No cuttings at the shale shakers

2.4.2 Preventive Measures

Bowes and Procter (1997) and Mitchell (2014) stated that the subsequent points/actions prevent stuck pipe incidents caused by mobile formations:

- OBM maintains in-gauge hole
- Raising the mud weight will hold the salt back and reduce the creeping rate
- Regular reaming and wiper trips of the salt interval

- Selection of low tripping speeds in sensitive sections
- Avoidance of high overpull
- When tripping back into problematic zones, reaming through them is advised
- Reduction of the open hole exposure time of these formations to a minimum and casing them off as fast as possible
- When drilling through salt formations, usage of a fully salt saturated mud will prevent salt layers from dissolving and mobilizing
- Bi-Center polycrystalline diamond compact (PDC) bits, as illustrated in Figure 6, are used to drill a larger diameter well than the diameter of the bit and stabilizers. This size increase aids to control troublesome zones by allowing more time to drill between the reaming intervals (Creative 2019).

Figure 6: Bi-center PDC bit (Creative 2019)

2.4.3 Freeing

If the drill string gets stuck due to the existence of a salt formation, Adelung et al. (1991) propose the following actions:

- While pulling upwards with the maximum allowable force, the spotting of a freshwater pill will dissolve the salt at the stuck point assuming that circulation is possible
- Avoid pulling too hard into the salt as this will pack-off the string entirely, and circulation can be lost
- The pill should be large enough to cover the BHA
- If an oil-based mud is used, pumping an unweighted spacer which contains water and detergent before the pill is advised
- In case that the pipe is still stuck after two hours, spotting a second fresh water pill is recommended
- Jarring in the opposite direction of the last movement should be considered as the last option. When jarring up no torque should be applied to the drill string, when jarring down the simultaneous application of torque is permitted.

2.5 Naturally over-pressured shale collapse

A naturally over-pressured shale is one with a natural pore pressure greater than the normal hydrostatic pressure gradient (Bowes and Procter 1997). This type of formation and its associated pipe-sticking problem, which is shown in Figure 7, is the result of geologic mechanisms like under-compaction, natural removal of the overburden rock due to weathering or uplift. When drilling with insufficient mud weight, these formations can become unstable causing the wellbore to collapse. The shale fragments accumulate, pack-off the BHA and consequently lead to a stuck pipe event (Schlumberger and Anadrill 1997).

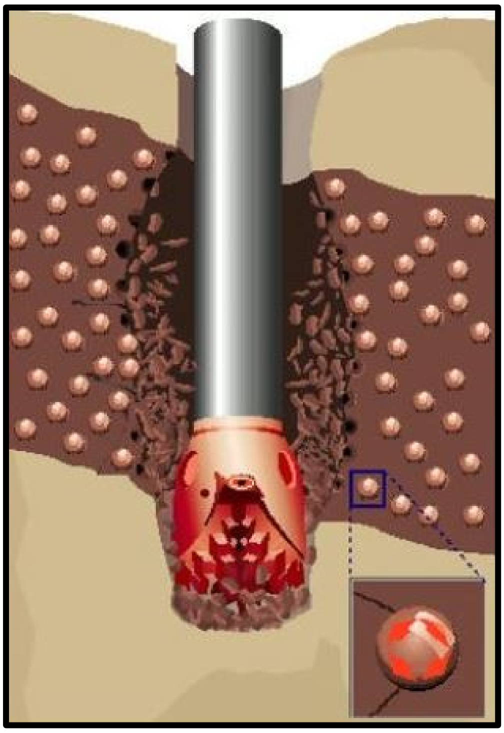

Figure 7: Naturally over-pressured shale collapse (Bowes and Procter 1997)

2.5.1 Indications

According to Bowes and Procter (1997), this stuck pipe mechanism can be recognized by:

- Increase of torque and drag
- Large amounts of brittle, not hydrated, large-sized cavings and cuttings on the shaker screens
- Gas levels and D-exponent increase
- Restricted circulation
- Increase in ROP, due to the chip hold down effect[5]

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[5] The pressure difference between hydrostatic mud column and formation pressure will decrease

2.5.2 Preventive measures

To prevent the occurrence of this stuck pipe mechanism, it must be ensured, that the mud weight is sufficient all the times as it supports the formation and prevents it from dropping into the wellbore. The amount of gas has to be monitored closely to know pore pressure trends. Another method to predict the pore pressure trend is the D-exponent. According to Alyasi and Wahab, Dhiya Al Din Abd (2015) the D-exponent is used to extrapolate drilling parameters. By its use, the encountering of an over-pressured zone can be forecasted. Thereby, the mud weight can be adapted and the risk of getting stuck lowered. (Bowes and Procter 1997)

2.5.3 Freeing

In case the drill string gets stuck, the same steps should be followed as when getting stuck due to unconsolidated formations. The procedure is given at 2.1.3.

2.6 Fractured and faulted formations

In tectonically active zones, the formation is often fractured. Normally, this condition shows up near faults. The encountered rocks during drilling are broken into fragments due to the tectonic stresses. If such a zone is encountered during the well construction stage, the loose pieces of rock can fall into the wellbore and block the drill string. According to Mitchell (2014), brittle formations like limestone tend to fracture more than flexible ones like clay. Due to vibrations during drilling, the formation can fall into the borehole even if the rock pieces are bonded together. This sticking mechanism, illustrated in Figure 8, typically occurs during drilling and is often related to fractured limestone (Adelung et al. 1991).

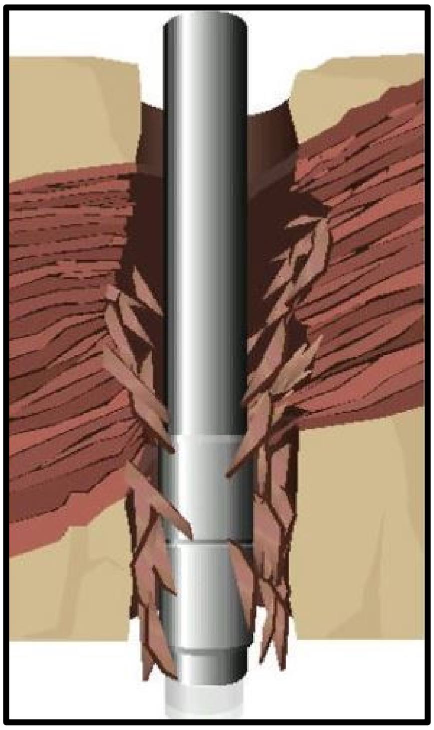

Figure 8: Fractured and faulted formations (Adelung et al. 1991)

2.6.1 Indications

Bowes and Procter (1997) mention that this type of stuck pipe comes about during drilling or while moving the drill string up or down and declares that first recognizable symptoms are:

- Sudden increase and erratic torque and drag
- Large and irregular rock fragments with sharp edges are observed on the shale shakers before getting stuck
- Circulation may be restricted before getting stuck
- Overpull is identified
- This sticking mechanism can occur instantly, and therefore the right mitigation actions have to be conducted very quick
- This type of problem may appear and disappear and will be hard to attribute to a certain depth because the bridging material is moving up or down the wellbore (Mitchell 2014).

2.6.2 Preventive measures

As this kind of stuck pipe often occurs due to vibrations during drilling, the revolutions per minute (RPM) and the BHA design should be selected in a way to prevent their occurrence. Additionally, shock absorbers can be installed in the drill string. As the drill string touches the wellbore wall and can cause the formation material to fall in the well, the tripping speed should be lowered before the BHA enters sensitive sections. In general, fractured formations need some time to become stable and have to be reamed with care before drilling can proceed. To avoid pressure surges, smooth movement of the drill string and limited tripping speed are essential. Before tripping, the hole has to be circulated clean and reaming jobs should be anticipated during trips (Adelung et al. 1991).

2.6.3 Freeing

To release the string which became stuck due to fractured formations, (Bowes and Procter 1997) propose the following procedure:

- If the string got stuck during upward movement, jarring down with no torque application is advised.
- In case there are no restrictions, circulation can be maintained at the maximum rate
- When the pack-off happened during RIH, jarring upwards to break up the formation fragments is recommended
- It should be tried to preserve circulation all the time
- Pumping high viscosity pills aid in cleaning the wellbore
- The pumping of an acid pill is useful when the string got stuck in limestone
- Mitchell (2014) points out that low-resonance frequency tools are helpful to break up debris and reduce friction

- When the drill string is released, large chunks of formation need to be broken up and circulated out of the well. This is achieved by getting the material below the bit where it can be drilled up (Mitchell 2014).

2.7 Inadequate hole cleaning

Mitchell (2014) states that insufficient hole cleaning is the major reason for a large percentage of all stuck pipe, especially in high-angle wells. He mentions a study in the North Sea that accounts for 33% of stuck pipe events to poor hole cleaning and declares that any pack-off and bridge type sticking mechanism has hole clean-up as a concern. Therefore, the most essential element to construct a wellbore in a trouble-free way is adequate hole cleaning. To ensure adequate removal of cuttings and rock fragments, mud rheology, pump rate, annular velocity, drill pipe eccentricity, cuttings bed properties, ROP and RPM must be considered. If the created cuttings at the bit are not cleaned-out effectively up the annulus and out of the wellbore, they will pile-up around the bit and drill collars when the pumps are turned off for making a connection. The rock particles get packed together and stick to the borehole wall and drill pipe causing stuck pipe. In deviated wells, rock particles accumulate at the lower side of the wellbore and form a cuttings bed. When pulling the BHA through these solids deposits, the drill string gets stuck as they increase the torque and drag and decrease the transfer of WOB. Another way of getting stuck occurs when cavings fall down or avalanche[6] in the annular area and pack-off the drill string. If hole cleaning is performed satisfactory, an adequate amount of rock particles is removed from the well, allowing the drill string to move freely. To visualize the mechanism of getting stuck due to inadequate hole cleaning, Figure 9 is headed. The most common motives for solids not being removed properly are a too low annular flow rate, inadequate mud properties, inappropriate circulation time and an unsatisfactory flow regime (Bowes and Procter 1997).

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[6] In wells with over 65 degrees inclination, more cuttings settle very fast and slide down the wellbore as a unit

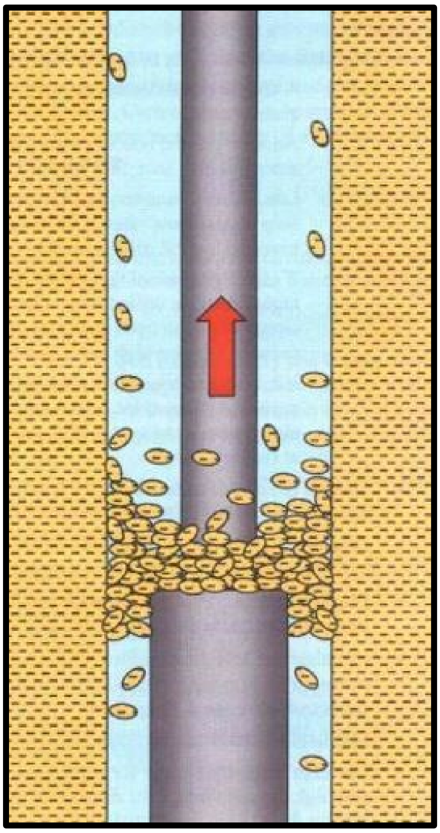

Figure 9: Inadequate hole cleaning (Mitchell 2014)

2.7.1 Indications

Insufficient hole cleaning shows up long before the drill string becomes stuck. According to Adelung et al. (1991) and Mitchell (2014), the rig crew must be aware of the following warning signs of an upcoming stuck pipe event due to inadequate solids removal. For a better overview, these symptoms are divided into three categories:

Connection:

- Pump pressure to break circulation increase as the difference in hydrostatic pressure between the clean mud in the drill string and the cuttings-laden mud in the annulus intensifies.
- Mitchell (2014) states that a reduction of off-bottom torque indicates that the hole is loading up with cuttings
- Increasing overpull when picking up off the slips as cuttings have settled across the BHA

Tripping:

- Excessive overpulls are increasing in the deviated hole section
- Overpulls due to excessive drag when passing through cuttings beds
- Reducing overpull during pumping
- Overpulls inside casing
- Decreasing slack-off weights indicate cutting beds (Aljubran et al. 2017)

Drilling:

- Poor weight transfer to the bit
- Increasing torque and drag; can also become erratic when the cuttings start to obstruct pipe motion
- Toolface is problematic to orientate
- Increase of mud weight and PV
- Presence of re-ground cuttings[7] indicate that hole cleaning is not sufficient (Aljubran et al. 2017)
- Not enough cuttings return for the current ROP
- Steady decrease in ROP; As the bottom hole pressure increases due to additional cuttings, the apparent rock strength increases which results in a lower ROP[8]
- Irregular cuttings return
- Inconsistent pump pressure and pump pressure spikes as the hole occasionally bridges
- Abnormal pump pressure trends as more cuttings are present in the annulus; This trend must not be confused with the normal pressure trend due to increasing depth.
- Changing pump pressure due to sliding cuttings beds
- Surface fluid volume decreases less than expected; When the additional hole is created, it must be filled with mud. In case that cuttings beds build up, the surface volume will not decline as planned. If the cuttings beds are unsettled by pipe rotation and the cuttings are removed from the wellbore, the active surface volume will decrease as the volume of rock fragments needs to be replaced, see Table 1.

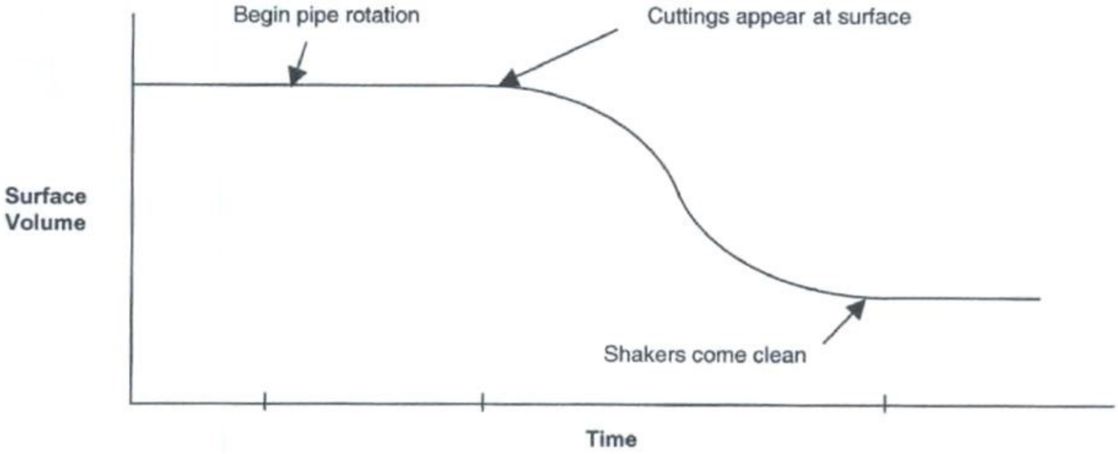

Table 1: Monitoring surface fluid volume (Mitchell 2014)

In Table 2 the following warning signs of a potential pack-off due to poor hole cleaning can be recognized:

- Increasing pump pressure while drilling while strokes per minute (SPM) are kept constant

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[7] Edges of cuttings are smoothed due repeated up- and downward movement and re-drilling

[8] Chip hold down effect

- Torque, drag and pump pressure are fluctuating
- Increasing pump pressure to break circulation after a connection
- Increasing overpull picking up off the slips after a connection (peaks in hook load)

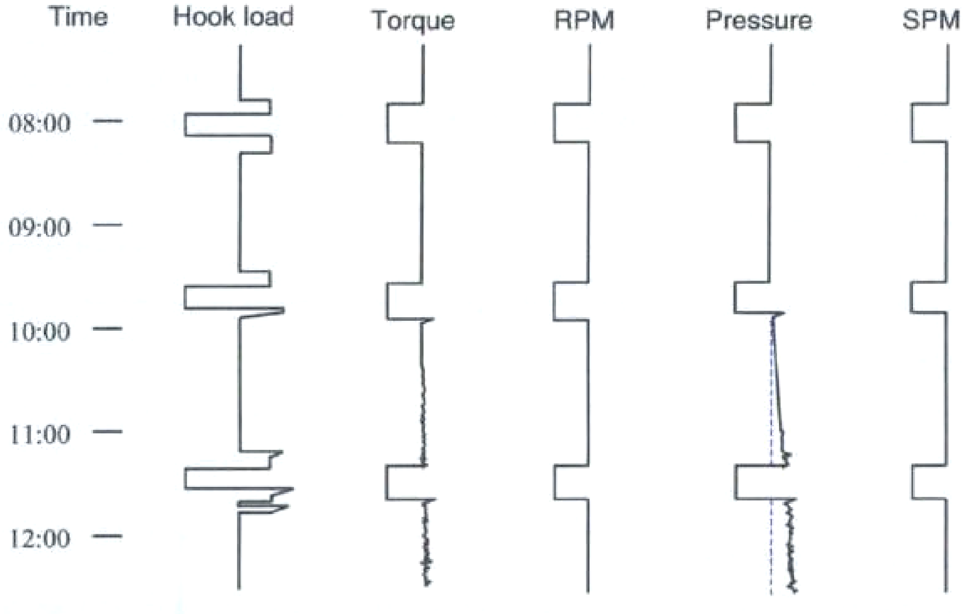

Table 2: Trends for poor hole cleaning (Mitchell 2014)

2.7.2 Preventive measures

Bowes and Procter (1997) recommend to concentrate on the subsequent points to avoid packing-off the drill string:

- Connection time should be minimized
- According to Aljubran et al. (2017), the use of a continuous circulating system reduces the likelihood of getting stuck while making a connection as the cuttings will not start to settle and form a cuttings bed in a deviated well
- Ensure adequate annular velocity
- Take into consideration the use of a third mud pump and connect it in parallel to achieve higher flowrates
- To prevent a plugged bit or pack-off and ensure that the bit is not buried in cuttings when circulation is commenced, it is suitable to circulate the last three stands down to bottom (Mitchell 2014).
- To achieve higher flowrates, it should be considered to use larger drill pipes
- Adjustment of the mud properties[9]
- Reciprocation of the string
- *Frequent wiper trips with full circulation and bit rotation must be used to clean the hole* (Mitchell 2014). Axial movement alone is not enough to unsettle the cuttings beds.
- Mitchell (2014) also recommends the establishment of over-pull limits. Thereby, it can be prevented that the pipe is pulled too hard into a pack-off and cannot be

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[9] YP, PV

freed with downward movement. If difficulty is encountered, pulling into it shortly and backing-off with step-by-step increasing force while ascertaining free downward movement is proposed. This procedure is reiterated until the obstacle is passed or the overpull limit is achieved.

- Monitoring of hole cleaning trends: Free rotating weight, pick-up weight, slack-off weight, off bottom torque, on bottom torque and circulating pressures
- Evaluation of torque and drag trends
- Recording of tight spots during connections or trips
- Make a spreadsheet to observe volume reduction of the active fluid system
- Make sure circulation times are sufficient
- In order to find the maximum rate of penetration with a particular flowrate or to obtain the minimum required flowrate for a specific ROP, hole cleaning charts can be checked. An example for 8,5'' holes is shown in Table 3. By using PV and YP of the mud, the rheology factor (RF) is obtained from the left chart. From Table 4 the angle factor (AF) can be taken. Afterwards the transport index (TI) can be calculated with equation (1). Then the computed TI is used in the right chart in Table 3 to receive the minimum required flowrate or the maximum allowable ROP to ensure proper hole cleaning. A general rule of thumb was proposed by Mitchell (2014): In 17,5'' hole 1000gpm or more are necessary, in 12,25'' hole at least 750gpm and in 8,5'' hole 500gpm or beyond.

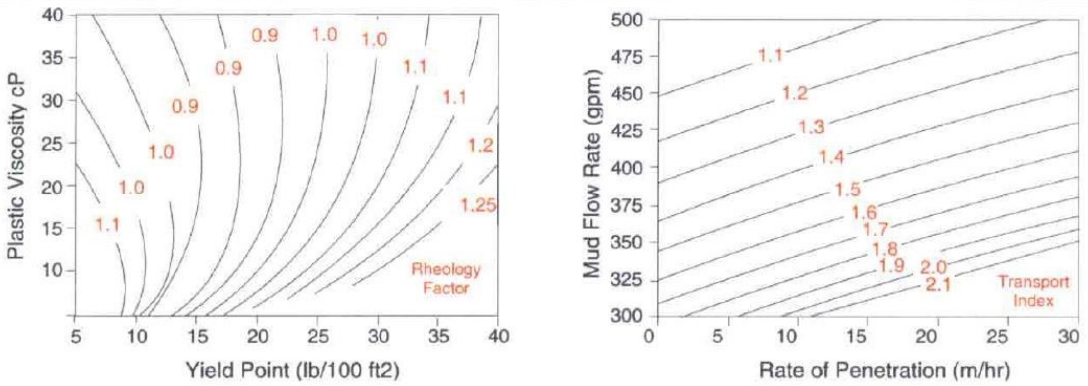
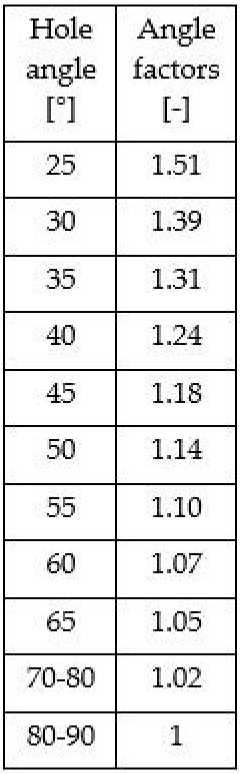


Table 3: Hole cleaning charts for 8,5'' holes (Mitchell 2014)



Hole angle [°]	Angle factors [-]
25	1.51
30	1.39
35	1.31
40	1.24
45	1.18
50	1.14
55	1.10
60	1.07
65	1.05
70-80	1.02
80-90	1

Table 4: Angle factors (Mitchell 2014)

$$TI = \frac{RF * AF * MW}{8.33} \tag{1}$$

where MW is the mud weight in lbs/gallon.

2.7.3 Freeing

If poor hole cleaning is the reason for the stuck pipe condition, Adelung et al. (1991) propose to conduct the following actions:

- Bleeding off any trapped pressure is the first step in any kind of pack-off. Otherwise, the piston effect will reduce the amount of applied downward force.
- Afterwards, Mitchell (2014) proposes to apply 200 to 500psi, then torqueing and slumping the pipe to try to re-establish circulation. The application of torque assists in re-establishing circulation and pipe movement.
- As the majority of pack-offs occurs when moving the drill string out of the hole, it should be tried to work the string downwards. Though in directional wells it can also happen that pack-off happens during RIH. In this case, the string should be moved up not down.
- As torsional and tensile stresses are additive, jarring upwards during torque application is not recommended. Jarring down while applying torque is acceptable because torsional stress and compressive stress are not additive.

- Once circulation is set up, it is essential to clean the wellbore before any further operation.
- Once the circulation is re-established, cuttings/cavings are cleaned best by pumping high viscosity pill in nearly vertical wells; in deviated wells start with circulating low viscosity pills followed by more viscous ones in order to disturb cuttings beds
- During the pumping of pills, rotation of the drill string further improves the situation as more solid particles are unsettled.

2.7.4 Hole cleaning in vertical wells

To determine the effectiveness of hole cleaning, the rig crew monitors drilling parameters and trends and the returns on the shale shakers. In the work of Mitchell (2014) also two mathematical techniques to assess hole cleaning efficiency in vertical wells are presented:

The volumetric cuttings concentration is given by equation (2) :

$$Volumetric\ cuttings\ concentration = \frac{Volume\ of\ cuttings\ in\ annulus}{Total\ annular\ volume} \qquad (2)$$

To achieve better hole cleaning and thereby a lower volumetric cuttings concentration, it must be ensured that the cuttings are lifted up the well. Conversely, the cuttings fall down through the mud due gravity at a certain speed called slip velocity, given by equation (4). To make sure the cuttings are carried upwards, the annular velocity must be higher than the slip velocity. The transport ratio, given by equation (3) is the second method to express hole cleaning efficiency:

$$Transport\ ratio = {}^{v_c}/_{v_s} \qquad (3)$$

where $v_c = velocity\ of\ cutting = v_a - v_s$

and $v_a = annular\ velocity = {}^{flow\ rate}/_{flow\ area}$

$$v_s = slip\ velocity = \sqrt{\frac{2gd_c(\rho_c - \rho_f)}{1.12\rho_f}} \qquad (4)$$

where g=gravitational constant, d_c=diameter of cutting, ρ_c=density of cutting and ρ_f=density of fluid;

Mitchell (2014) states that anything that increases the transport ratio improves hole cleaning. The best way of doing this is to decrease the slip velocity by increasing the mud density, see equation (4). Raising the annular velocity or reducing the size of the cuttings by selecting a proper bit are also ways to increase the transport ratio. As it is tried to keep the mud weight as low as possible for economic reasons, commonly the annular velocity and rheologic parameters are modified.

In the following points the most influencing factors in vertical wells with a short description according to Mitchell (2014) are listed:

- Mud weight: Most influential parameter regarding hole cleaning; If the mud weight is zero, there would be no support possible from annular velocity.
- Annular velocity[10]: It is the second most influential parameter affecting hole cleaning efficiency in a vertical well. The annular velocity provides a lifting force as it slips past the cuttings.
- Fluid rheology: An increase of YP[11] results in better hole cleaning but PV not, as it is the additional force needed to cause the mud to flow
- Flow profile is controlled by the hole size. The larger the hole size, the lower the velocity at the walls. An illustration of the flow profile in a vertical well is shown in Figure 10.

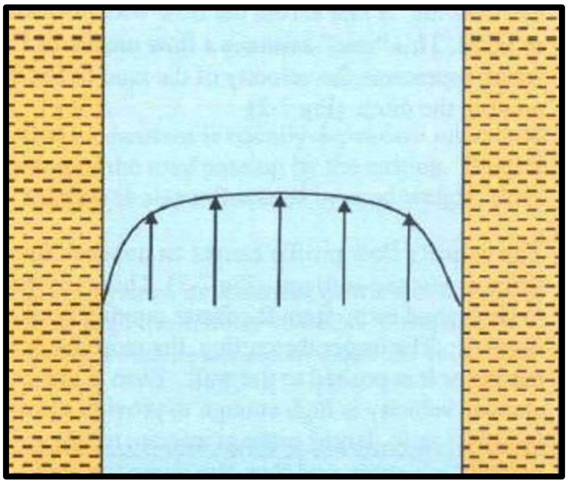


Figure 10: Flow profile in a vertical well (Mitchell 2014)

- Flow regime: Laminar flow regime is preferred in vertical wells.
- Cutting size, shape and quantity
- ROP influences the size and amount of cuttings produced. At high ROP the size and the number of cuttings will be larger.
- Pipe rotation improves hole cleaning by pushing cuttings away from the wall back into the high-velocity region.
- Eccentricity leads to a flat flow profile on the side with no pipe and thereby lowers the cuttings transport ratio.

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[10] As the annular velocity is not constant across the diameter of the wellbore, average annular velocity is meant

[11] Force required to initiate flow

2.7.5 Hole cleaning in directional wells

In directional wells, hole cleaning problems can always be anticipated (Mitchell 2014).

Mitchell (2014) states that the same elements impacting hole cleaning in vertical wells also influence hole cleaning in inclined boreholes, but due to the growth of cuttings beds and quick settling at some angles, there are major differences in how these factors apply. The axial component of the slip velocity decreases with increasing inclination angles. Thus, the transport ratio gets less applicable to estimate hole cleaning efficiency. In deviated wellbores, the height of the cuttings beds designates where sticking is most likely to happen, and therefore the focus is on dispersing these beds and bringing the cuttings into suspension. As cuttings beds lead to stuck pipe due to pack-offs, they are the cause of most drilling problems in directional wells and therefore need to be prevented. The hole cleaning ratio (HCR), see equation (5), and the minimum transport velocity[12] (MTV) are approaches to evaluate hole cleaning efficiency in directional wells by using the height of the cuttings beds. If HCR > 1 there will be no problems, but as this ratio decreases the tendency to become stuck grows. A study in the North Sea indicates when the HCR was less than 0,5, stuck pipe always occurred and no troubles took place when HCR was greater than 1,1. To sum up, under normal conditions half the annular area can be filled with cuttings bed. The MTV increases with increasing inclination up to 65° and then starts to decrease if the angle is getting larger.

$$HCR = \frac{H}{H_{crit}} \tag{5}$$

Where H_{crit} is the maximum allowable cuttings bed height the BHA can be moved through without getting stuck and H is the height of the annular space above the cuttings bed[13];

In the subsequent section the most influencing factors and their major findings according to Mitchell (2014) will be given:

- Inclination angle: Cuttings beds begin to establish at inclination angles above 30°. If the angle is less than 45°, these beds will slide down the wellbore if the pumps are turned off, see Figure 11. At angles up to 65° the cuttings beds permanently glide down, even when circulating. The cuttings beds become immobile when the angle exceeds 65°. The combination of sliding beds and rapid settling make the 45°-55° angle hole sections the hardest to clean.

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[12] Expresses the velocity required to initiate cuttings transport

[13] Also called free region height

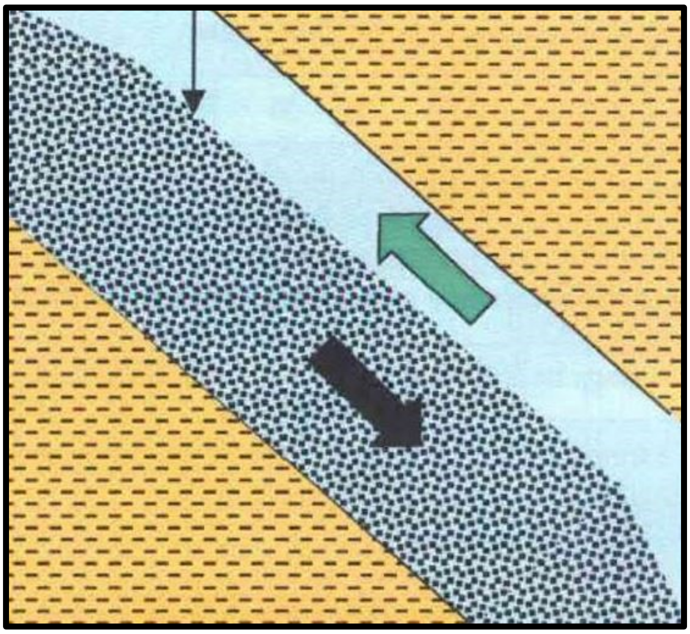

Figure 11: Sliding cuttings beds (Mitchell 2014)

- Mud properties: As can be seen in Table 5, a heavier mud makes it easier to erode the cuttings beds. Thus, the beds are smaller when a heavier mud is used. As the YP and PV of the mud decrease and the flow behavior index[14] (n) increases, cleaning in high angle sections is improved. *The intermediate viscosity mud performs the best at any angle and at all laminar flow rates when drill pipe eccentricity exists (Mitchell 2014).*

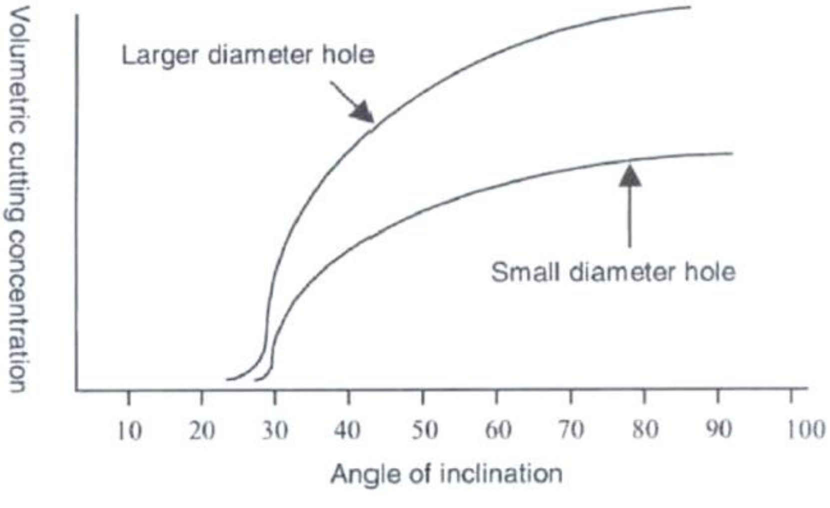

Table 5: Effect of mud weight on cuttings bed height (Mitchell 2014)

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[14] Exponent in Herschel Bulkey rheological fluid model; If n = 1 the fluid is Newtonian and if n < 1 the fluid is pseudoplastic or shear-thinning

- Flow regime: Laminar flow is less effective in dislocating the cuttings beds than turbulent flow. Therefore, Adari et al. (2000) advise that turbulent flow is desirable for angles above 55°. Laminar flow is preferable for angles below 45° because the reduction of the slip velocity is dictating in vertical wells. However, it must be added that in the absence of pipe rotation cuttings beds will always be present, regardless of how high the flow rate is.
- ROP impacts the size and amount of cuttings and hole cleaning will become problematic as more cuttings are present in the annulus. However, this does not affect the cuttings bed height. The beds reach a so-called steady-state height irrespective of the ROP. When stopping to drill, the solids in the vertical section of the wellbore will be removed. However, the cuttings beds in the deviated hole section will persist. Thus, monitoring the shale shakers for hole cleaning gives the wrong impression. The shaker screens will get clean after all suspended cuttings are out of the well, but the cuttings beds remain undisturbed. Rotation of the drill string is required to unsettle the beds (Azar and Sanchez 1997).
- The annular flow rate is the most critical parameter for hole cleaning in directional wells. The annular velocity must be above MTV to prevent cuttings from settling and mitigate the formation of cuttings beds.
- Pipe rotation adequately disturbs cuttings beds and reduces MTV. Without drill string rotation, cuttings beds will be formed. Thus, with increasing inclination, the influence of pipe rotation becomes more important. It is also significant that cuttings beds will not cause any problems when rotating the string. Usually, the pipe gets stuck when it is pulled out of the hole, as the BHA passes through cuttings accumulations. The influence of pipe rotation increases as the inclination angle increases. When drilling in sliding mode or drilling with coiled tubing, the drill stem is not rotated. This leads to the formation of cuttings beds (Azar and Sanchez 1997).
- In vertical wells pipe eccentricity influences hole cleaning only minimal, conversely, it has a substantial effect on the flow profile in directional wells. When the pipe is laying on the low side of the wellbore, the flow is turned away from the cuttings and thereby the hole cleaning efficiency decreased. The effect of eccentricity on hole cleaning is shown in Figure 12.

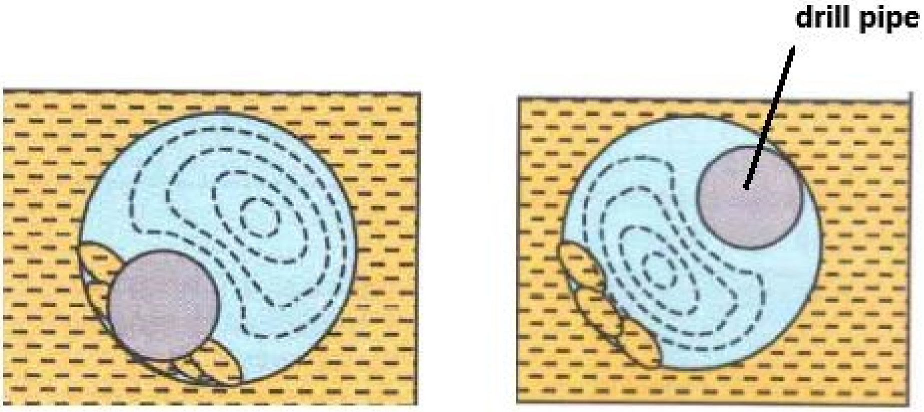

Figure 12: Effect of eccentricity on hole cleaning

- Hole diameter: Due to slower velocities, cutting beds are more likely in larger hole diameters.
- More time is needed to carry cuttings along an inclined borehole, thus with increasing inclination the time to clean the hole also goes up.

2.8 Problem-solving approach

Stuck pipe is a problem for the drilling industry. For any problem, there is a problem-solving approach that can be followed to efficiently and effectively solve the problem (Mitchell 2014). The definition or preparation of a plan is the first step in the problem-solving procedure. When the problem is well defined, it is easier to solve it. Thus, in the case of stuck pipe problems, it must be defined how and when sticking occurred. Afterwards, a plan with best-practices can be set-up to get out of the trouble. As final point, the lessons learned have to be analyzed and compiled with the aim of future improvement (Mitchell 2014).

By answering the four questions on the left side in Table 6, the most probable sticking mechanism can be identified:

Direction of pipe movement just before sticking?	**Pack-off or Bridge**	**Differential Pressure**	**Wellbore Geometry**
Moving up	2	0	2
Moving down	1	0	2
Static	2	2	0
Downward motion of pipe after sticking?			
Down free	0	0	2
Down restricted	1	0	2
Down impossible	0	0	0
Pipe rotation after sticking?			
Rotate free	0	0	2
Rotate restricted	2	0	2
Rotate impossible	0	0	0
Circulating pressure after sticking?			
Circulation free	0	2	2
Circulation restricted	2	0	0
Circulation impossible	2	0	0
Total points			

Table 6: Stuck pipe freeing worksheet (Mitchell 2014)

To better understand the application of Table 6, the following example is given: It is assumed that the pipe got stuck during POOH, no rotation or movement of the drill string is possible, and circulation cannot be achieved. With this information, the appropriate rows can be selected, as indicated in yellow in Table 7. Afterwards, the numbers in each column are summed up, and the column with the highest total number corresponds to the most probable sticking mechanism. In the illustrated example the column ''Pack-off or Bridge'' achieves the highest total number and therefore is the most likely sticking mechanism.

Direction of pipe movement just before sticking?	**Pack-off or Bridge**	**Differential Pressure**	**Wellbore Geometry**
Moving up	2	0	2
Moving down	1	0	2
Static	2	2	0
Downward motion of pipe after sticking?			
Down free	0	0	2
Down restricted	1	0	2
Down impossible	0	0	0
Pipe rotation after sticking?			
Rotate free	0	0	2
Rotate restricted	2	0	2
Rotate impossible	0	0	0
Circulating pressure after sticking?			
Circulation free	0	2	2
Circulation restricted	2	0	0
Circulation impossible	2	0	0
Total points	**6**	**0**	**4**

Table 7: Example how to use stuck pipe freeing worksheet

2.8.1 Flowchart for freeing solids induced pack-off

Out of the mentioned procedures for freeing solids induced stuck pipe in this chapter, the general procedures shown in Figure 13 were derived. The purpose of this flowchart is to quickly set the right action when running the training case on the simulator. On the basis of the present stuck pipe mechanism, the suitable steps are executed.

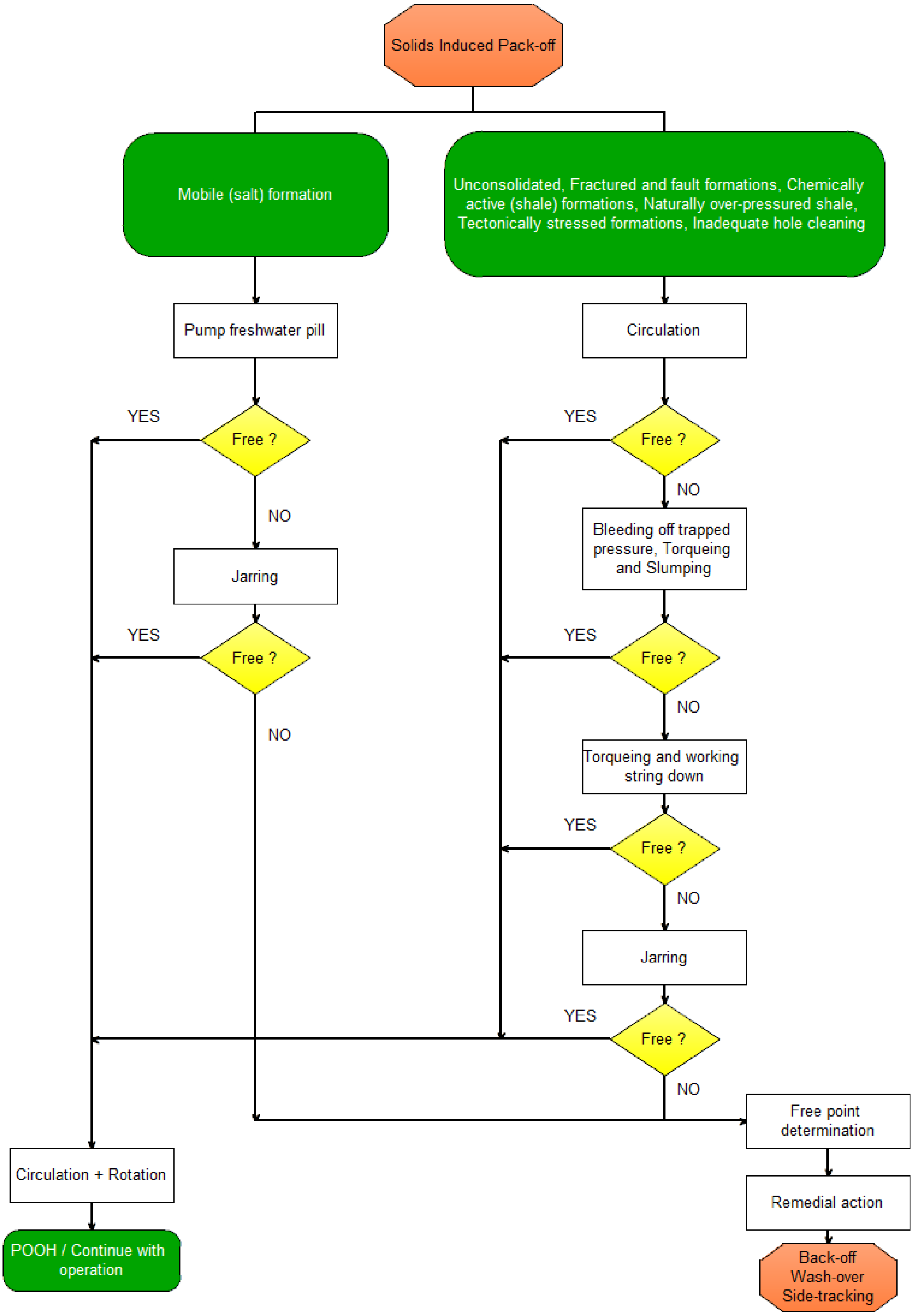

Figure 13: Flowchart for freeing solids induced stuck pipe (Draskovic 2017)

2.8.2 Summarized findings about solids induced stuck pipe mechanisms

The various mechanisms leading to solids induced pipe sticking, presented in Chapter 2, are always based on two main principles: hole collapse and inadequate hole cleaning. In most cases, it is the interaction between these two factors which cause the borehole to pack-off[15] or bridge[16] and consequently lead to the inability to move the drill string. In general, the symptoms indicated in Table 8 and Table 9 show up long before the drill string becomes stuck.

	Drag	Torque	Pressure	Other
Drilling	Increasing, erratic	Increasing, erratic	Increasing	Gradual decrease in ROP
Connection	Overpull off slips		Surge to start circulation	Back pressure before breaking connection
Tripping	Increasing, erratic Increasing set-down weight when tripping-in Overpull off slips			Back-flow

Table 8: Indications of stuck pipe (1) (Camargo 2011)

Shaker trends	Low cuttings return, erratic cuttings return, no cuttings, high cuttings return on fine shaker screens and desilter
Mud trends	Increasing PV and YP, increase of low gravity solids, increase of mud weight

Table 9: Indications of stuck pipe (2) (Camargo 2011)

In case, chemically active or mobile formations are present, the symptomatic torque and drag response is smoother. Moreover, large quantities of hydrated shale cuttings or soft clay balls which plug the shaker screens are typical signs for this kind of stuck pipe

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[15] Small-sized formation solids (cuttings, cavings) settle around the drill string; no string movement possible

[16] Medium to large pieces of formation build a "bridge" across the annular space; little to no string movement possible

event. In addition, a high funnel viscosity, YP, PV, CEC and content of low gravity solids is representative for this situation.

2.8.2.1 Tripping practice to prevent solids induced stuck pipe

Mitchell (2014) states in his work that the highest percentage of stuck pipe comes about while tripping. Before a trip can be performed, the hole and mud must be conditioned and the maximum overpull, tripping speed and potential problem zones have to be communicated to the driller. After a trip is projected, the hole and the mud must be prepared for it. This encompasses the removal of cuttings and cutting beds and reducing the PV as much as possible[17]. To prevent solids induced stuck pipe, Camargo (2011) proposes the subsequent circulation procedure:

- Consider pumping high-vis sweeps in low angle wells (<35°)
- Consider the alternate pumping of low-vis /high-vis sweeps in higher angle wells (>35°)
- Select an appropriate flowrate by using the hole cleaning charts expressed in Table 3.
- Maximize string motion when circulating the hole clean
- Circulation must not be stopped until all sweeps have returned to surface
- In case that the last sweep brings up excessive amounts of cuttings, hole cleaning operation must be continued.
- It is not recommended to circulate the whole time at the same position because the impact force of the pumped fluid can lead to washouts in that hole section. It must be tried to keep the drill string in motion so that the jets are not at the same depth for a long period (Mitchell 2014).

To ensure that the number of strokes required to clean the hole is sufficient, the following method is advised by Camargo (2011):

At first, the wellbore is divided into sections depending on hole size and inclination. Then the adjusted MD is calculated for each section with the help of equation (6). The circulating strokes factor (CSF) is taken from Table 10.

---

[17] PV is reduced to lower swab and surge pressures

$$Adjusted\ MD = Section\ length * CSF \tag{6}$$

Hole size	26″	17.5 – 16″	12.25″	8.5″
Angle of the interval				
0-35°	2	1.7	1.4	1.4
35-55°	2.5	2.5	1.8	1.6
>55°		3	1.2	1.7

Table 10: CSF to clean the hole (Camargo 2011)

By adding-up all adjusted MD values, the total adjusted MD is obtained. Subsequently, equation (7) can be used to compute the minimum circulating strokes to clean the hole. The bit to surface strokes are obtained through the employment of equation (8).

$$Min. Circ. Strokes = \frac{Total\ adjusted\ MD * Bit\ to\ surface\ strokes}{Measured\ depth} \tag{7}$$

$$Bit\ to\ surface\ strokes = \frac{Annular\ volume\ [bbl]}{Pump\ output\ [\frac{bbl}{stroke}]} \tag{8}$$

While conditioning the hole, torque, drag, returns on the shale shakers and pressure must be monitored closely to identify characteristic trends and indications for an upcoming stuck pipe event as indicated in Table 8 and Table 9.

Besides, wiper trips are employed to remove thick filter cakes, take away swelling or creeping formations and are useful to get information about the condition of the hole. Therefore, Mitchell (2014) declares that cost-cutting by minimizing the number of wiper trips is not smart as it most probably leads to stuck pipe.

Chapter 3 Drilling simulator work

The cooperation between the Department Petroleum Engineering and OMV has launched a Drilling Digitalization Lab at the Montanuniversity Leoben. The centerpiece of this lab is a state-of-the-art drilling simulator of the company eDrilling AS. In order to familiarize and become acquainted with the functions, the simulator with its user interface and a workflow guide about the implementation of a case are described in the following chapter. The framework of the simulator with its comprising applications is examined. Based on that a field manual to the implementation of a case was developed. The instructions in this guide are additionally illustrated by a flowchart.

3.1 Application of drilling simulators to reduce on the job training time

Drilling simulators are unique tools which offer enormous capabilities. Their beneficial utilization in several areas justifies the adoption of this technology in the oil and gas industry. The application of drilling simulators upfront the real drilling operation contributes to considerable cost savings as it aids in the selection of proper drilling equipment and its optimization. Additionally, the configuration of the wellbore can be improved and selected in a way to decrease the chance of encountering problems. Furthermore, the use of simulators allows the prediction of drilling parameters. Thereby, the comparison of measured loads while drilling with the predicted ones is enabled, and the onset of drilling problems can be detected. Without the simulators forecasted trend, the early detection of symptoms cannot be realized until the problem is grave. Another operational area of simulators is their use as diagnostic tools to post-analyze drilling problems. This aids in the comprehension and interpretation of the causes of particular issues (Child and Ward 1988).

Apart from the advantages mentioned above, drilling simulators also play an important role in the educational sector. In order to optimize the learning and development process and to shorten the needed training time, it is essential to incorporate up-to-date methods into the learning program. By the simulation of a drilling process in real-time trainees have to pay attention to possible errors and react appropriately to them. The teaching of best practices according to the encountered issues helps to turn trainees into highly qualified junior staff that meets all the new requirements. Lettner et al. (2019) claim that the use of state-of-the-art computer simulation together with a tailor-made teaching and learning software offer the basis for the skilled employee of the future. Moreover, it is stated in their work that the feedback of the students shows that the incorporation of simulators into the teaching process helps to memorize the course content better because the underlying principles are understood. To sum up, the virtual drilling of wells improves the crew’s skills and knowledge which makes it very attractive to new people coming into the industry. The potential to reduce the NPT during operations is one of the significant advantages for operators and service companies.

Hodgson and Hassard (2006) state in their work that drilling simulators lead to a reduction of the learning curve of drilling operations. By simulating the drilling operation, inefficiencies and potential problems can be detected. This allows the replacement of poor practices with best practices, thereby accelerating learning and achieving better performance during the real operation. The authors mention that especially in innovative well programs where new technology is in use or when getting on challenging operations it is beneficial to use drilling simulators to accelerate the learning experience. The movement from "Drilling the well on paper" to "Drilling the well on simulator" requires much more interaction of the team which contributes to better performance (Hodgson and Hassard 2006).

Mirhaj et al. (2013) mentioned the cost of 500 000 USD/day when a new driller is using the rig site for educational purposes. Alternatively, the same training imposes costs of 20 000 USD/day when conducted in a virtual environment. From this, it can be concluded that the training on simulators is much cheaper.

According to Mirhaj et al. (2013), the training on simulators adds value to operations because of the following bullet points:

- Maximum experience in a short time
- Training with scenarios that cannot be faced on the rig in a particular time
- Increase of the training efficiency as the teaching is provided 1:1
- Drilling crew that has been trained with this educational method worked more efficient in real operations
- Reduction of the risk during real operations by upfront simulation
- Increase of revenue by avoiding troubles like stuck pipe due to pack-off and lost circulation or treating them in a more efficient way
- Capability to detect downhole problems in advance before the situation gets out of control
- Well can be drilled in a shorter time

3.2 Framework of the eDrilling AS simulator

In the following section the system of the eDrilling simulator, the functions, and experiences from its use will be explained.

According to Rommetveit et al. (2007b), eDrilling is a new and cutting-edge system for real-time drilling simulation and 3D visualization. It provides the technology features for modeling, supervision, optimization, diagnostics, visualization, and control of the drilling process. The system which is controlled from a remote drilling expert center is owned by Teresoft, a leading provider of drilling and well performance applications. Teresoft with Morten Bjørnsen as the director is owned by the HitecVision private equity investment company and is settled in Stavanger in Norway. By providing integrated and dynamic drilling and well performance solutions which aid in planning, preparing, controlling and evaluating drilling operations, eDrilling follows their mission of saving costs, increasing efficiency and improving the safety of drilling operations. This is supported by close cooperation with exploration and production companies, operators, and service companies (eDrilling 2019).

The simulator of this company is capable to dynamically model the entire drilling process in real-time. It gives reactions of the well to actions from drilling installations, drill string and drilling fluid and thereby simulates drilling incidents in a realistic way. To be able to simulate the drilling process of a certain well, it is necessary to feed the simulator with data regarding rig, wellbore, drill string, drilling fluid and geology. These inputs are used to run the simulator models which form the background of the simulator. According to Rommetveit et al. (2007b), they are the result of gathered knowledge from research, development, and modeling in drilling. The different models, as shown in Table 11, encompass flow/hydraulics, temperature, torque&drag, vibrations, ROP, wellbore stability and pore pressure models. These modules interact with each other, and some of them work together with the mechanical earth model[18]. This setup then produces output parameters that can be displayed in different ways and acted upon by the user as he would do in the driller's cabin (Rommetveit et al. 2007b).

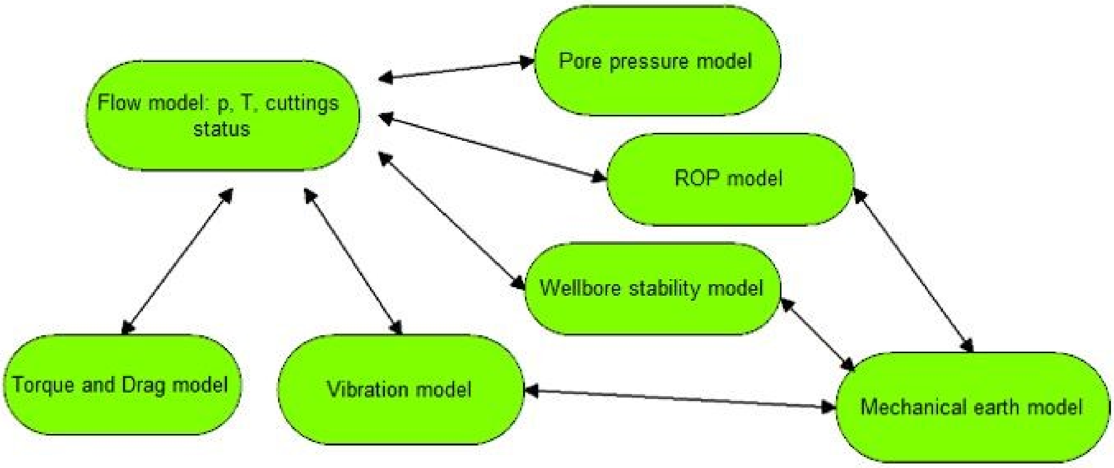

Table 11: Integrated models in the simulator (Rommetveit et al. 2007b)

The torque and drag model is utilized to calculate the WOB, bit torque from input parameters such as hook load and surface torque. It is also able to back-calculate the friction factor from the measured bottom hole and surface weights or torques. The ROP model incorporates formation parameters like compressive strength and formation pressure as well as drilling parameters like WOB, RPM, bottom hole pressure, bit properties, flow rate and viscosity for the calculations. The flow model handles the computation of the equivalent circulating density (ECD), equivalent static density (ESD)[19], temperature, pit volume and flow of cuttings (Rommetveit et al. 2007b).

The system of the simulator is established in an open manner where equipment suppliers, service companies, contractors, operators, and other authorized persons can connect to via standard interfaces like WITSML[20] (Rommetveit et al. 2007a).

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[18] numerical representation of the geomechanical properties of the subsurface formations such as density, porosity, fracture system, pore pressures, state of stress and rock mechanical properties

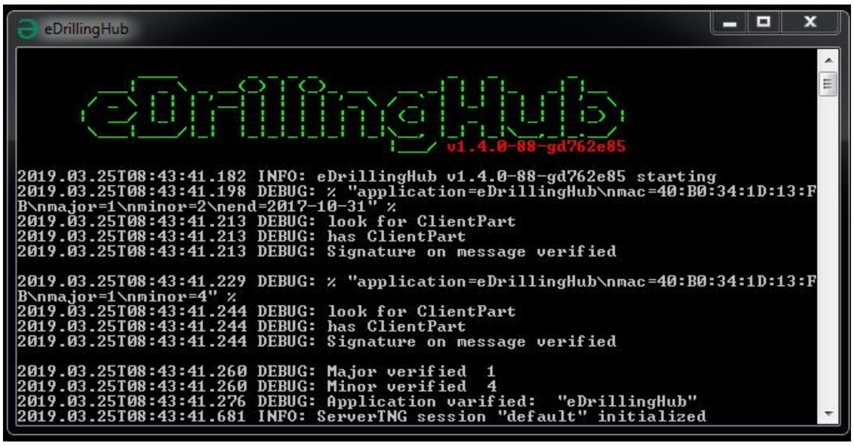
[19] We have ECD when circulating and for static conditions we have ESD

[20] WITSML is a standard for transferring technical data between parties in the petroleum industry

The eDrilling system is comprised of several different elements one of which is the drilling simulator. The drilling simulator itself is composed out of three main applications. These applications which are described in detail in the subsequent section of this thesis require a connection to Amazon Web Services (AWS) as the computations for the simulation are carried out in the cloud.

3.2.1 eDrillingHub

The eDrillingHub is used to connect the system to the AWS server where all the computations for the simulation are carried out. The running application is illustrated in Figure 14.



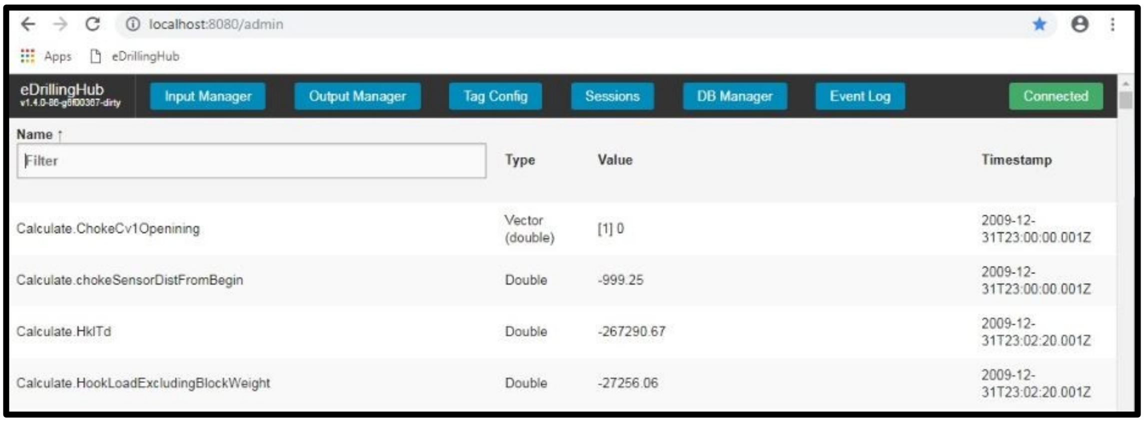
```
v1.4.0-88-gd762e85
2019.03.25T08:43:41.182 INFO: eDrillingHub v1.4.0-88-gd762e85 starting
2019.03.25T08:43:41.198 DEBUG: % "application=eDrillingHub\nmac=40:B0:34:1D:13:F
B\nmajor=1\nminor=2\nend=2017-10-31" %
2019.03.25T08:43:41.213 DEBUG: look for ClientPart
2019.03.25T08:43:41.213 DEBUG: has ClientPart
2019.03.25T08:43:41.213 DEBUG: Signature on message verified

2019.03.25T08:43:41.229 DEBUG: % "application=eDrillingHub\nmac=40:B0:34:1D:13:F
B\nmajor=1\nminor=4" %
2019.03.25T08:43:41.244 DEBUG: look for ClientPart
2019.03.25T08:43:41.244 DEBUG: has ClientPart
2019.03.25T08:43:41.244 DEBUG: Signature on message verified

2019.03.25T08:43:41.260 DEBUG: Major verified  1
2019.03.25T08:43:41.260 DEBUG: Minor verified  4
2019.03.25T08:43:41.276 DEBUG: Application varified:  "eDrillingHub"
2019.03.25T08:43:41.681 INFO: ServerTNG session "default" initialized
```

Figure 14: Launching the eDrillingHub

As soon as the eDrillingHub is connected to the server, the user interface in the form of a web page can be opened by typing the uniform resource locator (URL) http://localhost:8080/admin in a browser, see Figure 15. By clicking the red button with the labeling “Disconnected” in the right corner of the window, it will switch from to green and display the word “Connected” if the eDrillingHub is running. Thereby the web interface is connected to the server. When the simulation is started, all tags[21] can be watched and checked for changes. Examples for such tags are “Worker.Torque”, ”FM.calcProfileStation_cuttingsConcentration” or ”TD.bitDepthCalc”. On the top of the tag list, there is a filter, which allows the user to search for specific tag names. By clicking the red button with the labeling “Disconnected” in the right corner of the window, it will switch from to green and display the word “Connected” if the eDrillingHub is running. Thereby the web interface is connected to the server, and the model starts to receive new data on the specific tags.

---

[21] describes a parameter used by the simulation



Name ↑	Type	Value	Timestamp
Calculate.ChokeCv1Openining	Vector (double)	[1] 0	2009-12-31T23:00:00.001Z
Calculate.chokeSensorDistFromBegin	Double	-999.25	2009-12-31T23:00:00.001Z
Calculate.HklTd	Double	-267290.67	2009-12-31T23:02:20.001Z
Calculate.HookLoadExcludingBlockWeight	Double	-27256.06	2009-12-31T23:02:20.001Z

Figure 15: User interface web page

During the work on this thesis, a lot of changes in the configuration files had to be made. Once these files were modified, the user can also apply the eDrillingHub to check for errors in the syntax of the programming code. In case a mistake in the syntax occurred, the eDrillingHub displays a description of it in red color. However, the application does not have a built-in debugger which engages itself into the running process and informs about malfunctions which can be directly corrected. Merely, the file and the line of the error is shown. After the mistake was found and fixed by the user, the system has to be restarted and re-connected. This can be very time-consuming as all opened applications must be closed before the eDrillingHub can be started again. In case the system is not restarted after changes have been made a crash of all the other opened applications will follow.

3.2.2 wellSimInteract – OpenView2D

This application receives calculated parameters and trend data from the eDrillingHub and displays them over time or depth depending on the user's preference. Through its use, the generic parameters of the simulated drilling operation can be controlled. In general, it acts as engineering but also training system that delivers feedback from the well. It responds in real-time to the interactive input of the user and thereby grants insight and understanding of the well behavior at various conditions. Any planned well can be put into the platform via the Well Configuration Editor to study the dynamic well behavior and to verify that the plans and procedures are the best possible and safe. Within the use of this product, risk areas can be pre-run in the simulator, and the rig crew can train on potential malfunctions occurring during critical operations (eDrilling 2019).

According to eDrilling (2019) the user experiences the following advantages:

- Training and scenario developments
- Realistic training for engineers
- NPT reduction by better planning, improved risk management and improved decision support
- Manage risk both in planning and operation
- Chance to share simulations across teams and disciplines
- Insight and understanding of well behavior

- Enables optimization of drilling parameters to avoid troubles and improve performance and safety
- Improves drilling productivity and well planning accuracy

When OpenView2D has started the main window, as shown in Figure 16 appears. In this pane, the logs of the operation will be displayed once the simulation is started. The plots may be arranged according to their class, e.g. hydraulics, torque and drag, etc. by the panels on the right of the main screen. By right-clicking a window where plots can be added, named, styled and elsewhere adjusted will open. When the design is successfully reworked it can be saved, thus loaded in subsequent projects or sessions. The output curves such as pump pressure, HL, torque or ROP are displayed during the simulation and used to react upon by the user as he would have to do on the rig.

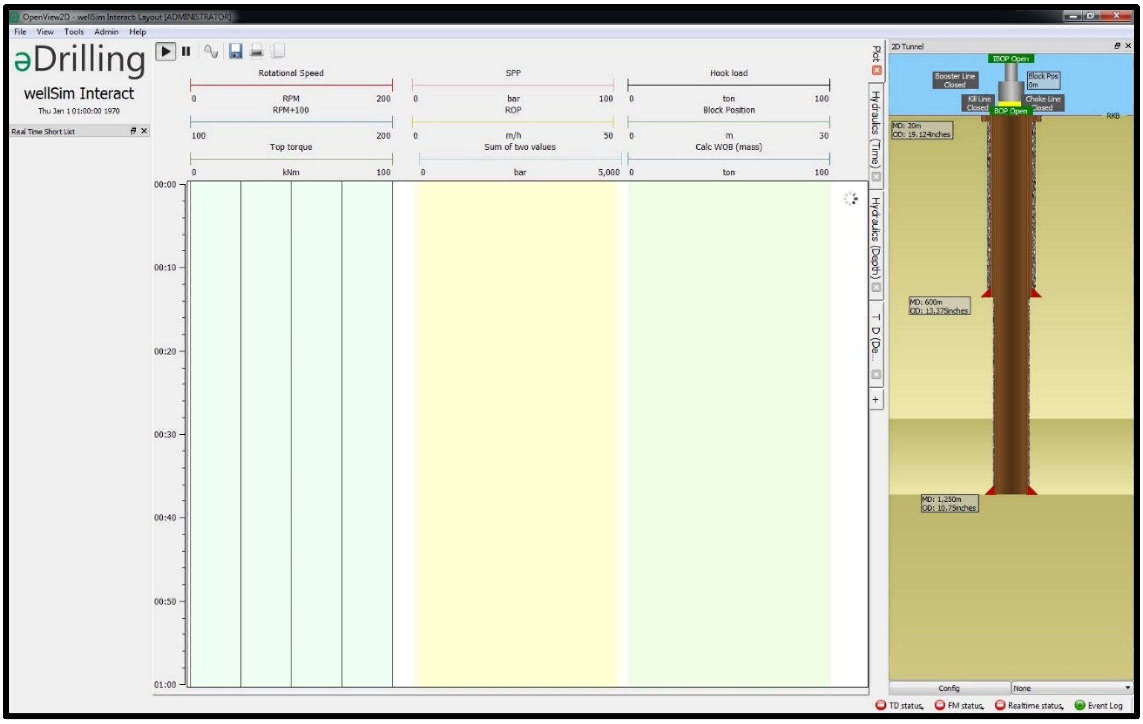


Figure 16: Main screen of OpenView2D

3.2.2.1 2D Tunnel

On the right side of the OpenView2D main window, the 2D Tunnel is arranged. It presents a 2D view of the wellbore with its installations depending on the entries in the Well Configuration Editor, see Figure 17. Some essential elements such as the different formations, casings/liners with its corresponding shoes and cement are displayed. Bronze lines represent casings/liners, and the casing shoes are indicated with red triangles. This tool also gives information about the casing sizes and depths in small boxes next to the casing/liner shoes. Moreover, the 2D tunnel can be used for data validation. If anything does not look properly, the mistake is recognized, and the corresponding inputs in the Well Configuration Editor can be revised.

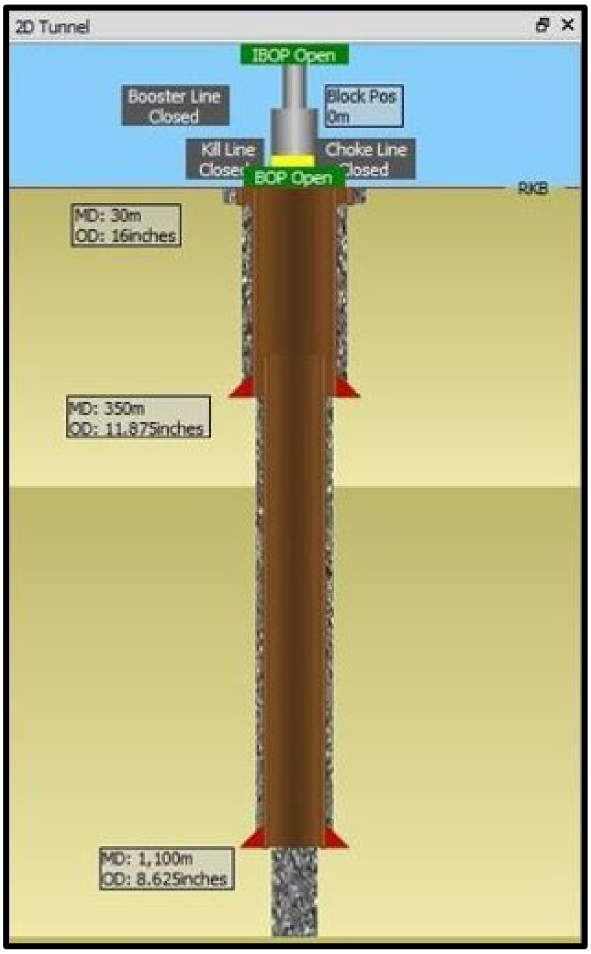
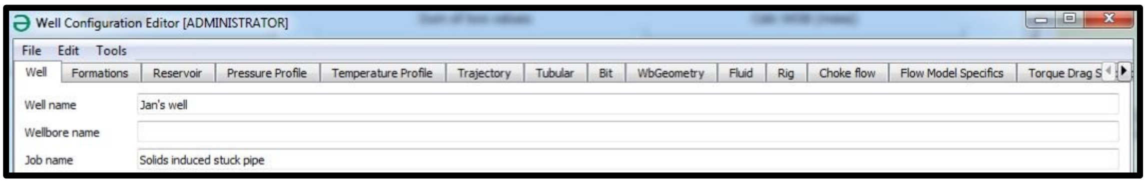


Figure 17: 2D Tunnel

3.2.2.2 Well Configuration Editor

Before any simulation can be run, it is necessary to provide the simulator all relevant information about the planned operation. It enables the development of custom-made scenarios which can be run in real-time and in time-lapse. Under Tools/Well Configuration Editor, the dialog box to define the wellbore is opened, as shown in Figure 18. Therein, numerous tabs have to be filled with information about the wellbore, drill string, and formation. When filling in the needed parameters, some tags will immediately give a visual representation of the data input. I.e., when entering the data in the tab Pressure Profile, the mud window will be automatically drawn on the right side of the window. After all, tabs are filled out the function Tools/Check data quality may be very useful in order to confirm that all entered data are valid. As this feature conducts a logical check and returns errors, the entered well-setup can be corrected. Except for the trajectory of the wellbore, the whole well configuration can be set up in the Well Configuration Editor. Though, the use of other well design tools such as Landmark may be helpful to accelerate the input process in the Well Configuration Editor. Once the well is configurated it must be sent to the server by clicking Edit/Send to server. These input parameters are then used by the models of the simulator in the cloud to calculate the output factors such as volumes, circulating pressures, torques and drags, etc. Afterward the editor can be closed. The 2D Tunnel in the main pane of OpenView2D will now represent a schematic of the wellbore.



Well name: Jan's well

Wellbore name:

Job name: Solids induced stuck pipe

Figure 18: Well configuration editor

3.2.2.3 Drilling Control

The primary function of Drilling Control is to run and control simulations. The program operates in a very user-friendly way, with an accent on button driven commands, see Figure 19. It enables the adjustment of the same drilling parameters as one would have in the real driller’s cabin.

Once the simulator is supplied with all necessary rig, well, formation and reservoir information, the system is ready to start the virtual drilling operation by clicking Tools/Drilling Control in the OpenView2D window. Starting the program takes exactly one minute and thirty-six seconds which can add up when trying out different things in the coding files and be quite annoying. The Drilling Control panel, as illustrated in Figure 19, enables to run through a specific scenario in real-time and in time-lapse. The simulation can be run faster, up to 10 times real time. The simulation control panel in the upper left corner of the window includes stop, play, replay and pause buttons which can be used while the case is played through. The Drilling Equipment Controls are used to control the drilling functionality. These parameters, such as block speed, RPM and pump rate, are not simulation parameters but represents the factors a driller can control from the control cabin. Just like in real operations the simulator will respond to changes of these parameters. The input values can be adjusted in two ways: By clicking on the pencil symbol, a numerical value can be typed in. It is also possible to alter the set value via the plus and minus icons next to the pencil symbol.

Total vol. pumped 0.38 m³
Total STK 16.78 STK
Bit depth 1,250.03 m
Well Depth 1,250.03 m

50.00 RPM
50.00 m/h
10.99 m/h
5.61 ton
1,000.00 l/min
0.00 l/min
0.00 m³
1,025.49 l/min
19.20 bar

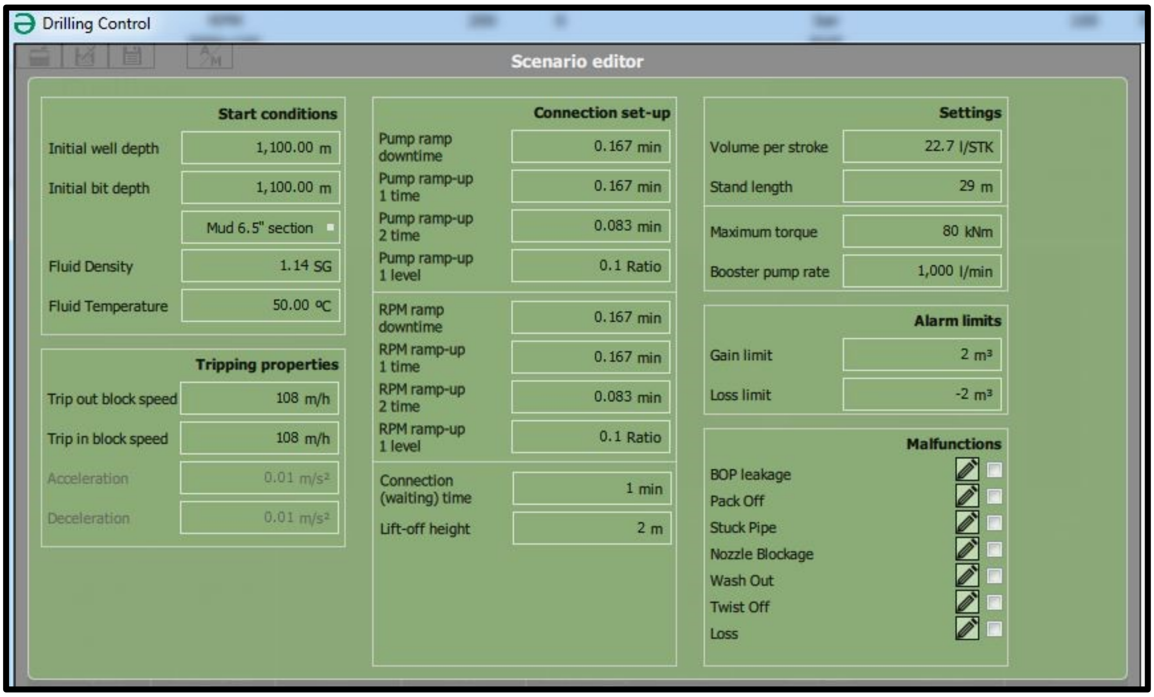
Block Pos 28.6653m
MD: 1,250m
OD: 10.75inches

Figure 19: Drilling control

The bar graphs in the simulation control panel consist of a green column, which represents the set point value and a yellow one which symbolizes the actual value. The magnitude of these data is numerically shown below the bar graphs or can be taken from the scale on the right which can be changed arbitrary by the user.

When selecting the magnitude of the block speed, it must be kept in mind that positive values stand for downward movement while negative ones will pull the string upwards. By clicking the connection button below the block speed column, connections will be automatically done by the system. The ROP, which can never be negative, is only updated if the block movement is positive and the bit is at bottom. Dynamic effects can cause that the ROP is not starting to update even if the above conditions are met. This case occurs during the compression of the drill string. The WOB is also calculated by the model. The tare button below the bar graph can be used to tare the weight at any time. However, the functionality of this button was not entirely understood during the writing of this thesis as the system is automatically taring the weight when the bit reaches the bottom of the hole. The Flow in is a simplification of pump control and represents the sum of all active pumps.

By clicking on the drillers chair symbol in the upper left corner the scenario editor, as indicated in Figure 20, will open. This editor permits the user to define the start conditions of the simulation, tripping limits, connection, and machine properties and activate malfunctions. Additionally, the user can change the fluid and its properties directly in the dashboard after the simulation has been started.



Start conditions
Initial well depth 1,100.00 m
Initial bit depth 1,100.00 m
Mud 6.5" section
Fluid Density 1.14 SG
Fluid Temperature 50.00 ºC

Tripping properties
Trip out block speed 108 m/h
Trip in block speed 108 m/h
Acceleration 0.01 m/s²
Deceleration 0.01 m/s²

Connection set-up
Pump ramp downtime 0.167 min
Pump ramp-up 1 time 0.167 min
Pump ramp-up 2 time 0.083 min
Pump ramp-up 1 level 0.1 Ratio
RPM ramp downtime 0.167 min
RPM ramp-up 1 time 0.167 min
RPM ramp-up 2 time 0.083 min
RPM ramp-up 1 level 0.1 Ratio
Connection (waiting) time 1 min
Lift-off height 2 m

Settings
Volume per stroke 22.7 l/STK
Stand length 29 m
Maximum torque 80 kNm
Booster pump rate 1,000 l/min

Alarm limits
Gain limit 2 m³
Loss limit -2 m³

Malfunctions
BOP leakage ☐
Pack Off ☐
Stuck Pipe ☐
Nozzle Blockage ☐
Wash Out ☐
Twist Off ☐
Loss ☐

Figure 20: Scenario editor

The 2D tunnel view on the right side of the Drilling control window, as also seen in the OpenView2D window, gives a 2D overview of the drilling operation. When the simulation is started a red and a blue line which indicate the pore and fracture pressure will show up. At the same time the ECD, which must be within the pore and fracture pressure, is designated by a green line. In Drilling Control, the 2D tunnel is equipped with flow lines which are shown as green/gray rectangles. The valves of these lines can be opened or closed by clicking the boxes. The green color stands for an opened valve while the grey color represents the closed state. To visualize the mentioned points Figure 19 is attached.

3.2.3 wellViz3D

The wellViz3D application is used for 3D visualization of the virtual wellbore and is connected to the wellSimInteract–OpenView2D application and the eDrillingHub. Real-time drilling data and real-time modeling is employed to monitor the drilling process and used as information to visualize what is going on in and around the wellbore. Through its use, it is possible to display details that are not visible in reality. Thereby a better understanding of the drilling process can be conveyed. The drilling rig which includes drill floor, derrick, and surface handling equipment as well as the virtually drilled wellbore with all its components like formations, trajectory, seismic, and tools are displayed in 3D, see Figure 21 (eDrilling 2019).

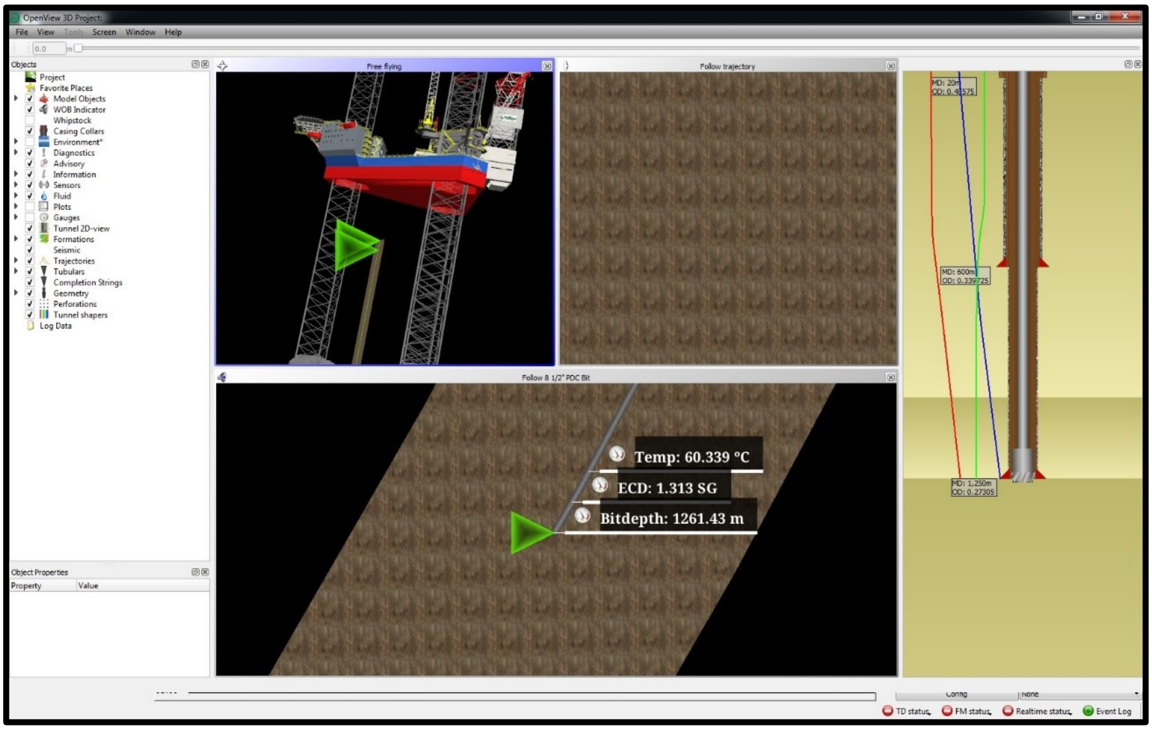


Figure 21: WellViz3D

As the idea of wellViz3D is to give the user a detailed, 3D real-time insight into the ongoing drilling activity, the developer enabled the following features:

- BHA visualization
- Imagining of info sources along the BHA or well such as sensors data, log data or fluid positions
- Three flying modes
- Free flying possibility
- Follow any BHA part
- Follow the trajectory
- Presentation of information along the BHA or wellbore
- Visualization of simulated data
- Displaying of fluid and cuttings flow
- WOB and drilling speed indications
- Capability to create plots
- Formation and seismic layers
- Proximity trajectories

By clicking on File/User Level/Set and selecting System Administrator the look of the drill string can be modified. In case the system requires a password, "admin" has to be entered. If a little time is spent to play with the program, a representation of the drill string, as shown in Figure 22, can be obtained.

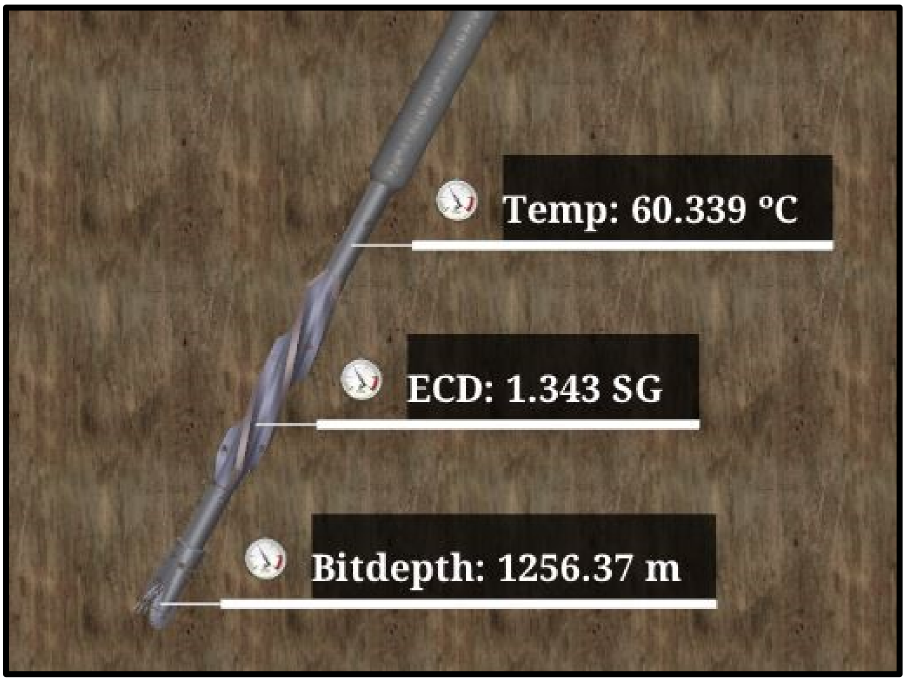


Figure 22: Drill string in WellViz3D after modification

3.2.4 Field manual for the implementation of a case

This chapter describes the implementation of a new case in the simulator. Step by step instructions will guide the user through the process and thereby assure a fast and efficient procedure.

Table 12 shows a sketch of the implementation workflow. As can be recognized, the first step is to start the application "eDrilling Hub". After the program is started, OpenView2D can be launched.

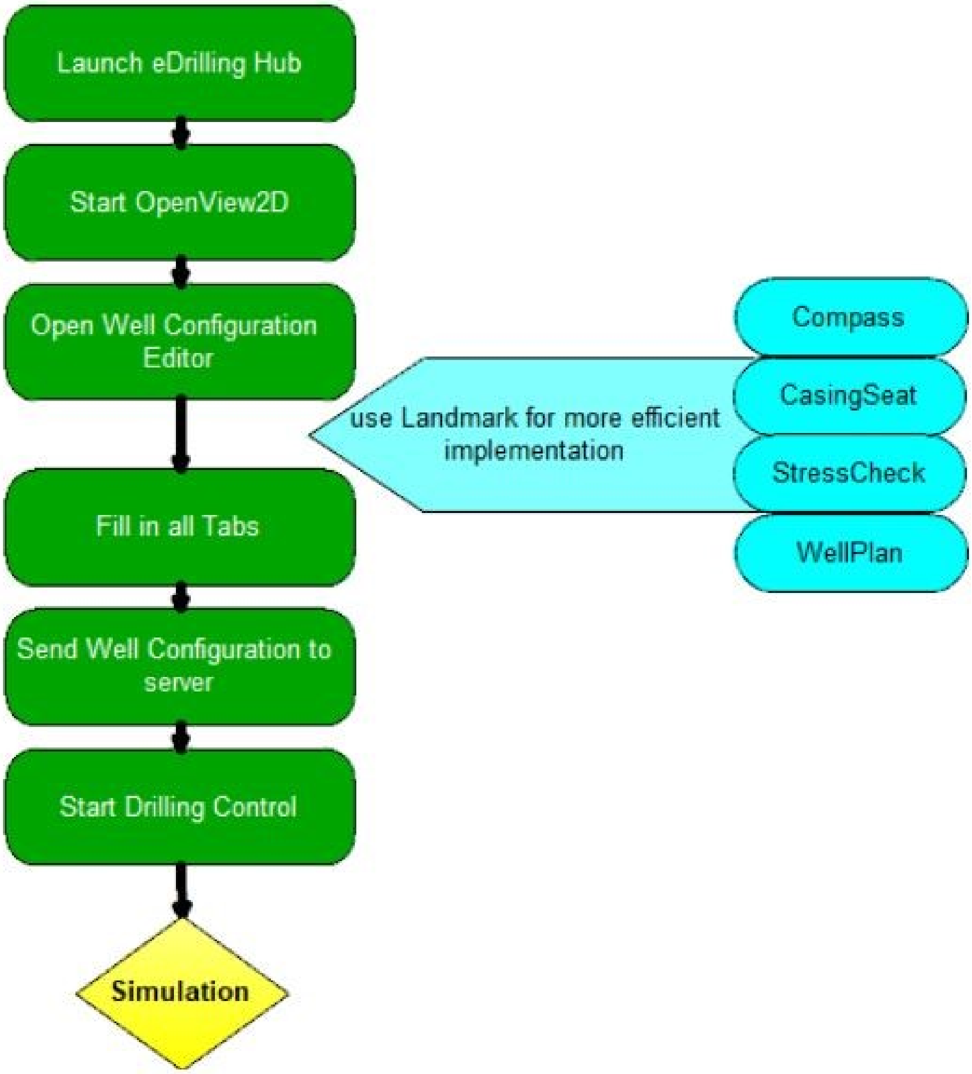
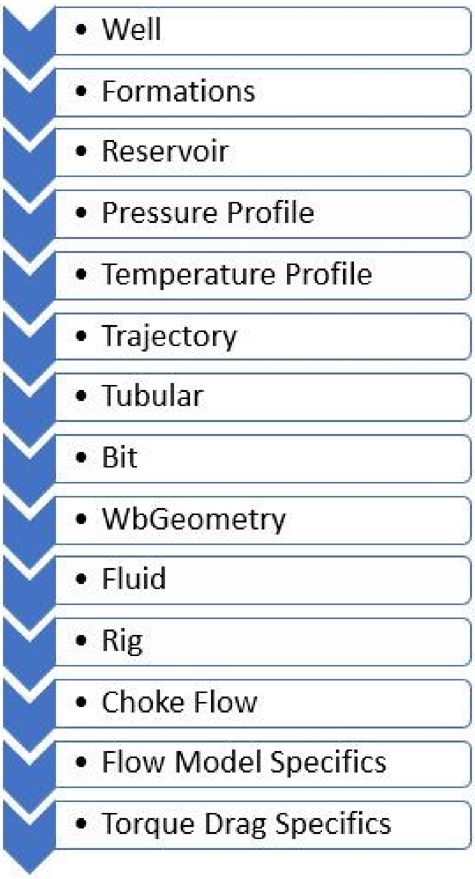


Table 12: Workflow of case implementation

In the main window of OpenView2D, the Well Configuration Editor is found when clicking the button "Tools". Before any simulation can be run, the tabs in the opened window must be filled with the required data. In Table 13, the workflow through the Well Configuration Editor is shown. A detailed description of the items is given below.



- Well
- Formations
- Reservoir
- Pressure Profile
- Temperature Profile
- Trajectory
- Tubular
- Bit
- WbGeometry
- Fluid
- Rig
- Choke Flow
- Flow Model Specifics
- Torque Drag Specifics

Table 13: Well configuration editor – workflow

3.2.4.1 Well

The first dialog box to fill is the "Well". The name of the well, wellbore and job have to be typed. The names can be selected depending on the user's preference.

3.2.4.2 Formations

To derive the appropriate responses like drilling proceeds through the subsurface, formation parameters must be entered into the system. The formation editor allows the user to construct a real or imaginary structure of rock layers that are encountered during drilling. The formation sequences have to be characterized by several parameters such as mineralogy, drilling and log responses in the editor. The input will be used by the models for calculation purposes and visualization. First of all, the name of the formation must be typed. Afterward, the formation type can be selected from a drop-down menu. By the selection of a type, the other columns will be filled automatically with the according configuration. In case this makeup does not fit, it can be modified by clicking into the corresponding box. In Table 14 the parameters needed for the simulation are described. In case any values are not known, -999,25 must be typed into the box. It must be kept in mind, that the first formation is the sea floor or ground, depending on whether it is an offshore or land rig.

Name	Arbitrary text identifying the formation
Type	Is selected from a drop-down menu
MD	Top of the formation measured along the trajectory
TVD	True vertical depth of the top of the formation measured from the RKB
EMod	Young's modulus of the rock; designates the drillability of the formation
Yield	Yield strength of the rock; designates the drillability of the formation
DrillingStrength	Indicates the amount of torque required to break the formation; typical range 10^7 – 10^9 Pa; designates the drillability of the formation
Friction	Specifies the friction of the cutter on bottom; range between 0 - 1
Density	Density of the rock; important for cuttings removal rate
Conductivity	Thermal conductivity; it is used by the flow model

Table 14: Description of important formation parameters

3.2.4.3 Reservoir

This tab just needs to be filled out if a reservoir is present. In other words, it is not mandatory to complete this dialog box. MD and TVD values are defined in the same way as in the "Formations" tab.

3.2.4.4 Pressure Profile

When entering the pore and pressure with its corresponding MD and TVD in the tab "Pressure Profile", the mud window will be automatically drawn on the right side of the window. This plot is based on the MD and can be used to verify the input data. Both MD and TVD have the RKB as the reference level. In case a value is not known, the value -999,25 must be entered.

3.2.4.5 Temperature Profile

This sheet describes the temperature of the wellbore. Either temperature data for MD or TVD must be entered. The values of the other column are defined by the input -999,25. After the temperature data are entered, the profile will be plotted on the left side of the window. In case the geothermal gradient is not available, it is possible to calculate it based on the formation temperature. This can be done by right-clicking into a cell in the "FormationTemp" column and selecting "Calculate Dynamic Profile". The principle can also be used the other way round. By right-clicking into a cell and choosing "Calculate Static", it is possible to calculate the formation temperature based on the geothermal gradient.

3.2.4.6 Trajectory

By the use of this window, the trajectory, which should include all the way to the final target depth, is defined. Therefore, the MD, TVD, inclination, and azimuth must be entered. If Northing/Easting is not known, there is the option to calculate these parameters by right-clicking into the Northing/Easting column from the remaining inputs. This input of the trajectory is considerably facilitated if a design software such as Landmark COMPASS™ is used. With the help of the Copy/Paste function, the designed well path can be imported into the can be used throughout, so data from spreadsheet applications can be copied, and pasted into the Well Configuration Editor. The plot of the trajectory which is created during data input can be used to verify the entered data. For further inspection, the plot can be spun.

3.2.4.7 Tubular

In this section, the drill string structure must be defined. As drill string design is a very complex process and needs accurate analysis before its implementation, the use of a design software is recommended. For the setup of the training case in this thesis, Landmark's WellPlan™ considerably facilitated the implementation of this procedure. After the design of the BHA is confirmed by proper analysis through auxiliary programs it can be put into the Simulator. The application "Tubular" in the "Well Configuration Editor" includes a tubular component library, which can be used to build the drill string. The library can be accessed by right-clicking into the table or through Tools/Tubular Library. It encompasses a selection of categories, which can be added and removed according to the needs of the user. The easiest way is to take the BHA constructed in WellPlan™ and rebuild it with the help of the tubular component library in the "Well Configuration Editor". When a component is selected from the library, all columns are filled automatically. In case this makeup does not fit, it can be modified by clicking into the corresponding box. To make the entry easier, critical parameters that could potentially lead to confusion are defined in Table 15.

TypeTubularComp	Text that describes the component
ODMx	Maximum outer diameter of the component
TypeIdentifier	Identifies the type of tubular

Table 15: Tubular – description of input parameters

3.2.4.8 Bit

In this sheet information about the bit are entered into the system. To edit the flow area of the bit, which is required for the calculations, two options exist. The first one uses the total flow area entered manually by ticking the box "Use Total Flow Area" and writing the corresponding value in the line below for the calculations. The second method requires the user to insert the number and diameter of the bit nozzles which are then automatically converted into a total flow area. Therefore, the box mentioned above has to be left blank.

3.2.4.9 WbGeometry

Additionally, the hole and casing sizes must be specified. In the tab "WbGeometry" the top and bottom of the specific casing/liner/hole as well as the corresponding diameters must be entered. The reference level for specifying the depth is again the RKB. Moreover, the user has to select whether the casing/liner has a shoe or not by ticking the box in the column "HasCasingShoe". "Roughness" describes the friction in relation to turbulent flow. If this data is lacking, this value can be set to 0. It must be kept in mind, that the intended section to drill and all subsequent ones must not be entered in this table.

3.2.4.10 Fluid

In this page, the drilling fluid to construct the desired section has to be specified. The system will propose a fluid which can be adapted by the user as desired.

3.2.4.11 Rig

This sheet designates the rig, mostly for informative objectives. The only parameter that is necessary for the calculations during the simulation process is the weight on block[22] as it is used to correct the hook load.

In addition, the length, diameter, and the vertical position of the flowlines needs to be specified in order to achieve reliable results during the simulation.

3.2.4.12 Choke Flow

In this tab, the configuration of the choke can be specified. As the developed training case in this thesis does not deal with well control incidents, all parameters in this tab were set to -999,25, which means "no value".

3.2.4.13 Fluid Model Specifics

The inputs on this page are mainly used to refine the flow model and to customize the configuration of the simulator. During the development of the training case, these inputs were left at the default values proposed by the system.

3.2.4.14 Torque and Drag Specifics

The parameters in this section serve the refinement of the torque and drag model and can also be left on the default values.

3.2.4.15 Flowchart for the implementation of a case

In Table 16 the workflow to implement a case in the simulator, as described in chapter 3.2.4, is expressed in the form of a flowchart.

---

[22] Corrected hook load = Measured hook load - Weight on block

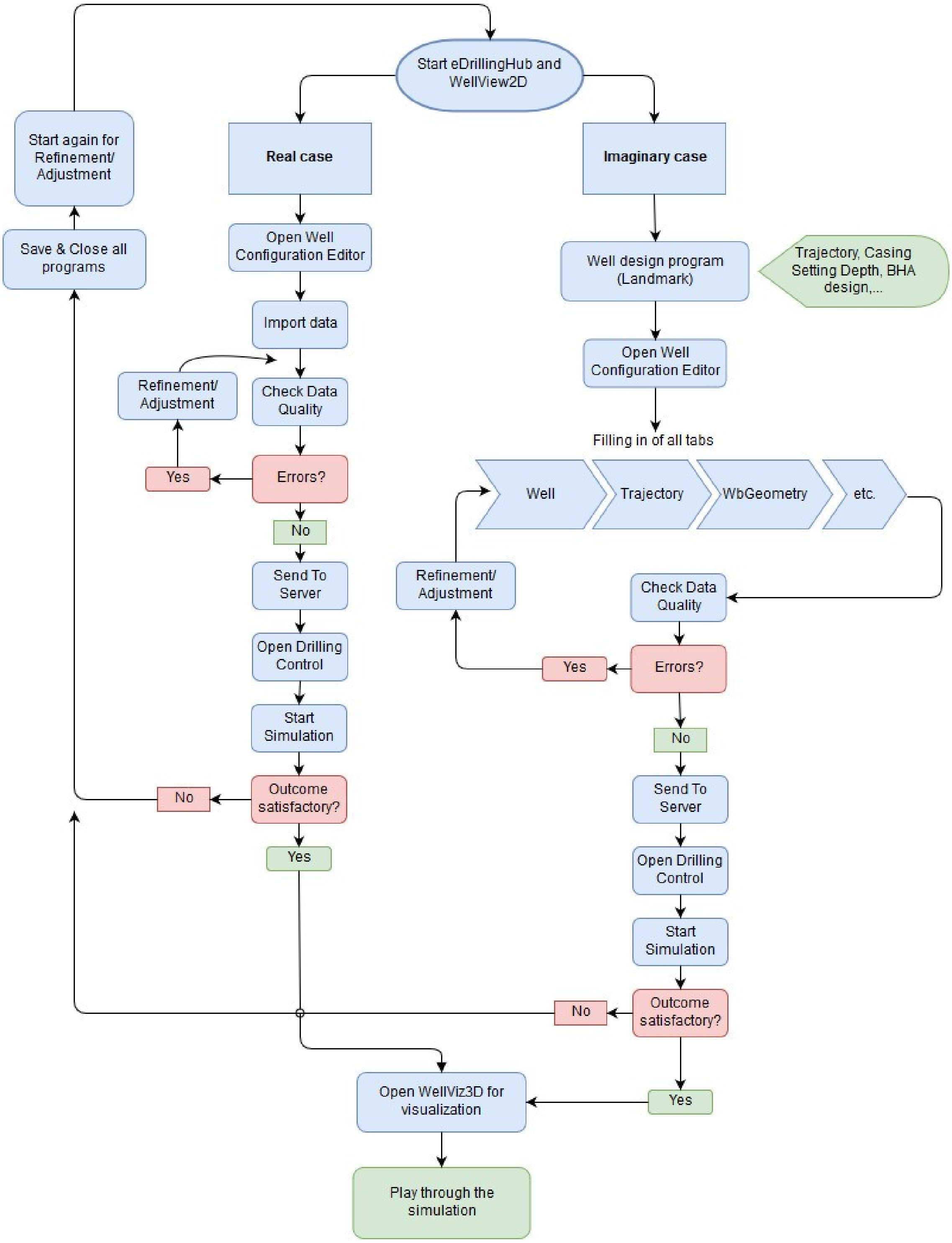


Table 16: Flowchart for the implementation of a case

After all tabs are filled out the function Tools/Check data quality may be very useful in order to confirm that all entered data are valid. As this feature conducts a logical check and returns errors, the entered well-setup can be corrected. Once the well is configurated it must be sent to the server by clicking Edit/Send to the server. Afterward the editor can be closed, and the control panel for the simulation can be started by clicking Tools/Drilling Control in the OpenView2D window. By performing the steps described in Table 17, the simulation can be started.

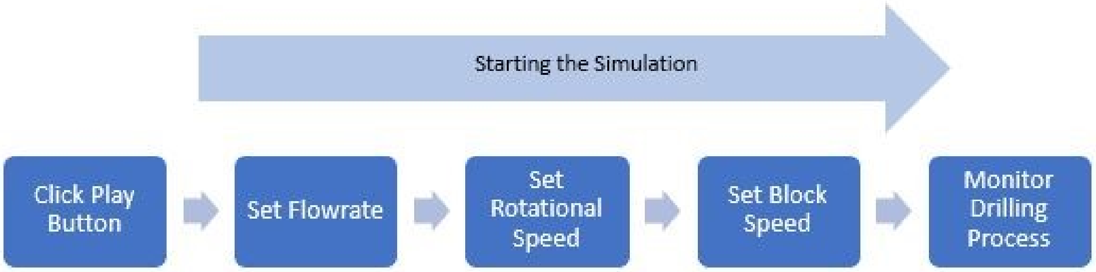


Table 17: Starting the simulation

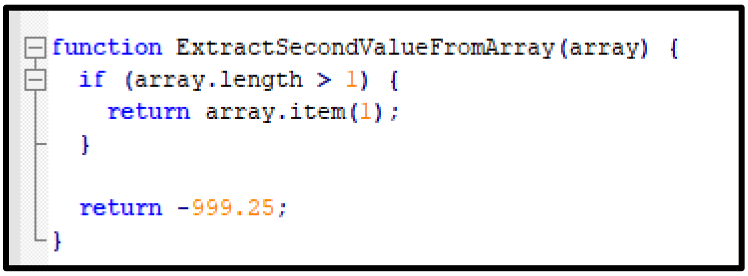
3.2.5 Interrelation of the background-working files

The eDrilling simulator has the advantage that it can be arbitrary extended with tailored functions and features. For this purpose, eight different files are located in the config directory where the eDrillingHub is installed. In order to be able to extend the functionality of the simulator, it is essential to know about the working principle and the interrelation of the background-working files. For this purpose, an explanation about these data sets and their interaction with the system was elaborated. The following chapter discusses the files calculate.js, sequence.json, and signals.json. Since these three files were essential for the implementation of the training case, their functionality and involvement in the simulation process are explained under a separate heading. In addition, examples show how these files can be extended, how their code works, and how they interact with the system.

Before starting the implementation, the eDrillingHub has to be closed. Because mistakes can be easily made during the modification of the files, it is highly recommended to make a backup of the original configuration. By the use of a text editor, these files can be opened, modified and extended to the user's discretion. After the corrections are done, the text files must be saved before the eDrillingHub is started. To run the model, it is necessary to start OpenView2D and to send the well configuration to the server.

3.2.5.1 Calculate.js

The first step to setup a customized calculation is to open the calculate.js file. Here the functions are defined at the discretion of the user. In Figure 23 an example is highlighted. A new calculation always starts with the expression “function”. Afterward an arbitrary name for it must be typed. Then the arguments which will be passed to the calculation are headed in brackets. In the main part of the function, the actual description of the calculation follows. In order to do so, the user can utilize loops, define variables and use the features of JavaScript. Depending on the preferences of the user, a double, int, bool, vector, matrix or string can be returned.

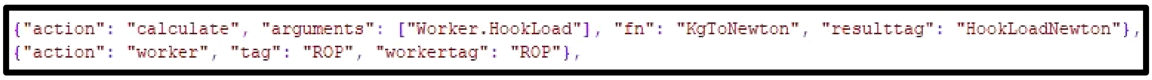


```
function ExtractSecondValueFromArray(array) {
  if (array.length > 1) {
    return array.item(1);
  }

  return -999.25;
}
```

Figure 23: Sample of a function in calculate.js

3.2.5.2 Sequence.json

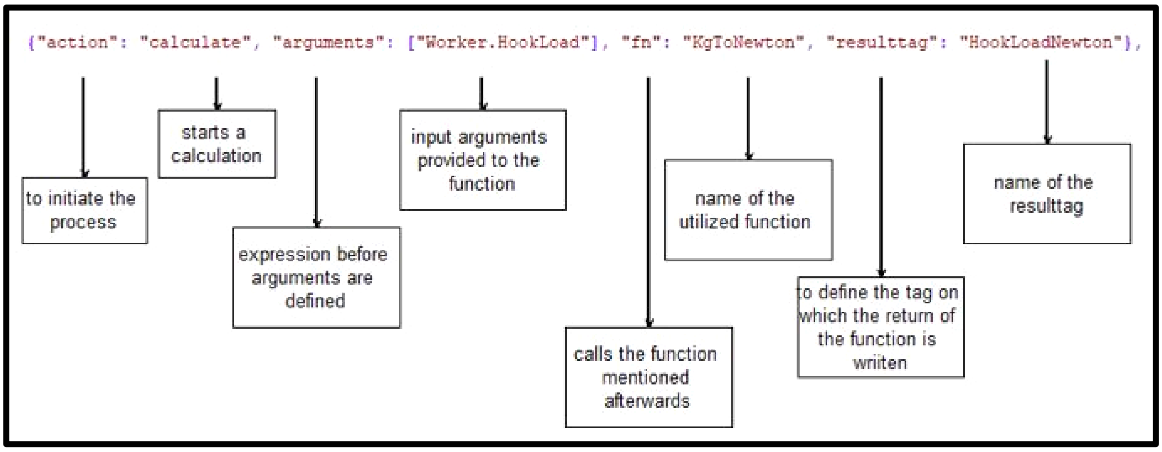
After defining the desired calculation in calculate.js, the next step is to open the sequence.json file which is also located in the config directory. Therein, the input sources and the model to run is stated. Two typical commands which are described in the following text are shown in Figure 24.



```
{"action": "calculate", "arguments": ["Worker.HookLoad"], "fn": "KgToNewton", "resulttag": "HookLoadNewton"},
{"action": "worker", "tag": "ROP", "workertag": "ROP"},
```

Figure 24: Content of the sequence.json file

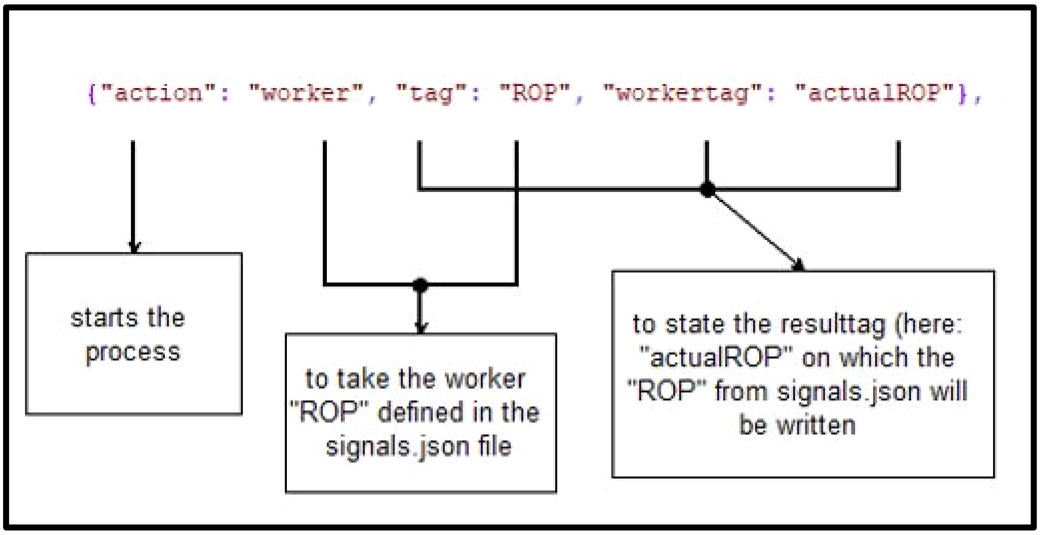
The term “action” is required to start the process. Then the expression “calculate” in combination with “arguments” delivers the input to the function defined behind the letters “fn”. Then the function “KgToNewton”, located in calculate.js, generates an output which will be written on the specified resulttag. The resulttag is then shown in the web page interface of the eDrillingHub. In order to understand the written better Figure 25 is attached.



```
{"action": "calculate", "arguments": ["Worker.HookLoad"], "fn": "KgToNewton", "resulttag": "HookLoadNewton"},
```

Figure 25: Description command in sequence.json (1)

The second command, as shown in Figure 24, only redirects a value to a resulttag, that is afterward shown in the eDrillingHub web interface, without any calculations. The term "action" is again initiating the process. The meaning of the other expressions is explained in Figure 26. As can be seen, the sequence.json file also accesses the signals.json and calculate.js file.

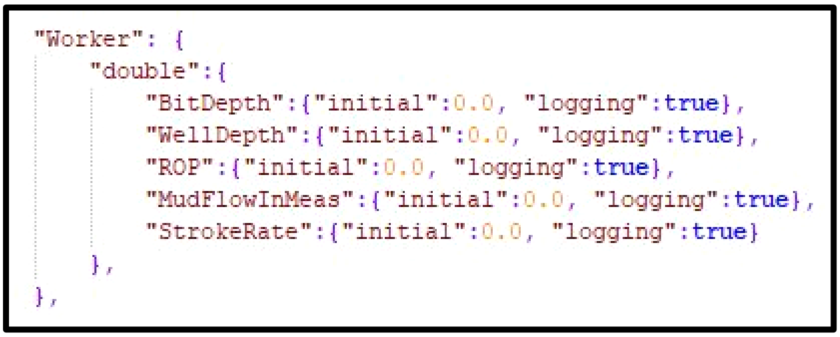


```
{"action": "worker", "tag": "ROP", "workertag": "actualROP"},
```

Figure 26: Description command in sequence.json (2)

3.2.5.3 Signals.json

For a better understanding, the following explanations refer to Figure 27. First, the type of variable of the worker has to be set, which in this case is a double. Afterward, the name of it as well as its initial value must be expressed. As a specific function was defined in the calculate.js file, it will be carried out for every time step. However, the value is not stored which is required to plot the history of it. Therefore, logging needs to be activated in signals.json by typing "true" next to the expression "logging".



```
"Worker": {
    "double":{
        "BitDepth":{"initial":0.0, "logging":true},
        "WellDepth":{"initial":0.0, "logging":true},
        "ROP":{"initial":0.0, "logging":true},
        "MudFlowInMeas":{"initial":0.0, "logging":true},
        "StrokeRate":{"initial":0.0, "logging":true}
    },
},
```

Figure 27: Commands in the signals.json file

Chapter 4 Development and implementation of the training case

The current best practices for solids induced stuck pipe prevention regarding scientific background from literature and operational experience from industry experts were evaluated in Chapter 2 and implemented into a training case on the simulator as part of this Chapter. Through this training scenario, industry personnel, university staff, and students can practice the right behaviour in the case of a solids induced stuck pipe event. As part of this scenario, the user has to detect an evolving stuck pipe event through specific symptoms and must react properly to them. If the preventive measures are not executed correctly and in time, the drill string gets stuck. Subsequently, the trainee must perform the correct procedure to release the drill string and be able to continue drilling. The procedures to be completed correspond to the best-practices and thus serve as a good teaching method to prepare users for stuck pipe situations during real drilling operations.

4.1 Description of the training case

After a detailed analysis of the different mechanisms leading to solids induced stuck pipe, it was found out that inadequate hole cleaning works best as a training scenario. Therefore, the symptoms summarized in Table 8 served as theoretical basis for the development. The next step was to integrate this concept into a JavaScript code in the calculate.js file which accesses the tags and changes them appropriately. For this reason, it was important to find the right tags or to integrate new ones into the system. In the following, the most important parts of the code and its associated tags will be expressed.

The tags that were already provided by the system of the simulator and accessed by the developed code are shown in Table 18.

Name of the Tag	Description
Worker.BitDepth	Depth of the bit
Worker.initialWellDepth	Initial well depth at which the simulation was started
FM.calcProfileStation_cuttingsConcentration	Cuttings concentration across the BHA
Worker.HookLoad	Actual hook load
Worker.TankVolume	Pumped volume of the selected fluid
Worker.RotationalSpeed	RPM
Worker.Torque	Maximum allowable torque; it was used to get the pipe stuck
Worker.WellDepth	Actual depth of the wellbore

TD.sppa	Standpipe pressure
TD.topTrqCalc	Actual Torque
TD.Static_friction	Friction between formation and drillstring
FM.pwdPresCalc	Calculated PWD during the simulation
FM.flowIn_kellyline_rate	Actual flowrate as set in the Drilling Control panel
FM.input_Wellbore_Hole_Diam	Actual hole size that is drilled

Table 18: Already implemented tags

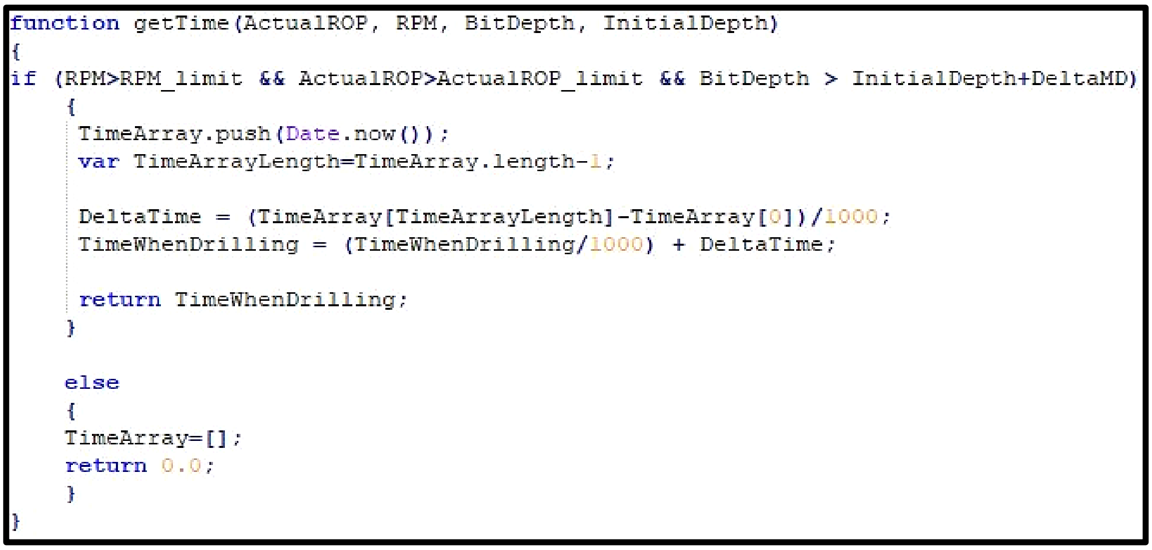
As the tags provided by the drilling simulator were not sufficient for the elaboration of a stuck pipe case, they had to be extended by self-created ones. An overview of the newly introduced tags is shown in Table 19.

Name of the Tag	Description
Worker.TotalDrillTime	The time when the bit is on bottom and producing hole; if this time reaches its set threshold, the drill string gets stuck
Worker.ellapsedTime	Kind of auxiliary time to calculate the TotalDrillTime; it starts to count when the user is drilling and is set to zero if the ROP falls below a certain threshold value
Worker.PickedUpOffBottom	Shows if driller has picked-up off bottom or not
Worker.RPMcorrect	RPM has to be in a certain range
Worker.Flowratecorrect	Flowrate has to be set suitably
Worker.PullingUpSlowly	String must be kept in motion
Worker.Takenaction	Confirms if all preventive actions were conducted
Worker.JarStrokeCount	Counts the number of upward jarrings
Worker.Overpull	Current hook load less the hook load when stuck
Worker.PillVolumeLow	Volume of low-vis pill pumped
Worker.PillVolumeHigh	Volume of high-vis pill pumped
Worker.AppliedWeight	Current hook load less the hook load when string got stuck
Worker.SlackOffCounter	Counts the number of downward jarrings

Worker.StuckStringTag	Shows the current condition of the drill string
Worker.ReleaseStringTag	Switches to true if all measures to release the string were done correctly

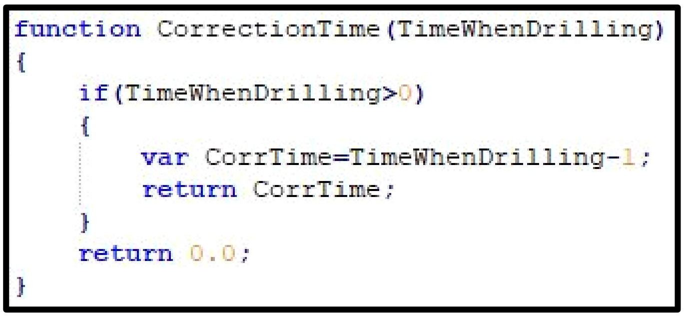
Table 19: Newly introduced tags

Once all required tags were available, the construction of the code commenced. In order to increase the amount of cuttings during drilling, a time function had to be implemented. The function “getTime”, as indicated in Figure 28, starts to count after a certain depth was drilled and if predefined ROP and RPM values are passed. In case the user stops drilling, this function returns zero and the corresponding time array is cleared. The returned value is handed over to the functions “CorrectionTime”, see Figure 29, which is just an auxiliary function accounting for the time when drilling is stopped, and “TotalDrill”, illustrated in Figure 30, that works out the actual spent drilling time. The return of the latter function is written on the tag “Worker.TotalDrillTime“ and used to handle the cuttings concentration.



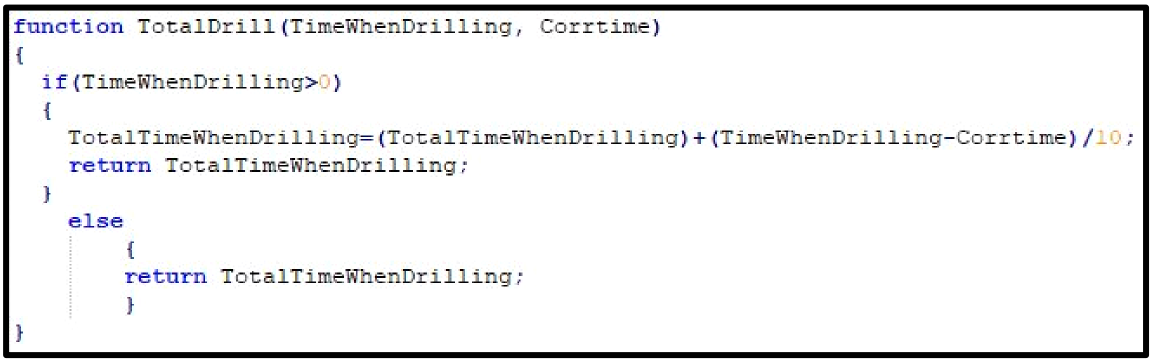
```
function getTime(ActualROP, RPM, BitDepth, InitialDepth)
{
if (RPM>RPM_limit && ActualROP>ActualROP_limit && BitDepth > InitialDepth+DeltaMD)
    {
     TimeArray.push(Date.now());
     var TimeArrayLength=TimeArray.length-1;

     DeltaTime = (TimeArray[TimeArrayLength]-TimeArray[0])/1000;
     TimeWhenDrilling = (TimeWhenDrilling/1000) + DeltaTime;

     return TimeWhenDrilling;
    }

    else
    {
    TimeArray=[];
    return 0.0;
    }
}
```

Figure 28: Time function just started if drilling



```
function CorrectionTime(TimeWhenDrilling)
{
    if(TimeWhenDrilling>0)
    {
        var CorrTime=TimeWhenDrilling-1;
        return CorrTime;
    }
    return 0.0;
}
```

Figure 29: Auxiliary time function



```
function TotalDrill(TimeWhenDrilling, Corrtime)
{
  if(TimeWhenDrilling>0)
  {
    TotalTimeWhenDrilling=(TotalTimeWhenDrilling)+(TimeWhenDrilling-Corrtime)/10;
    return TotalTimeWhenDrilling;
  }
    else
        {
        return TotalTimeWhenDrilling;
        }
}
```

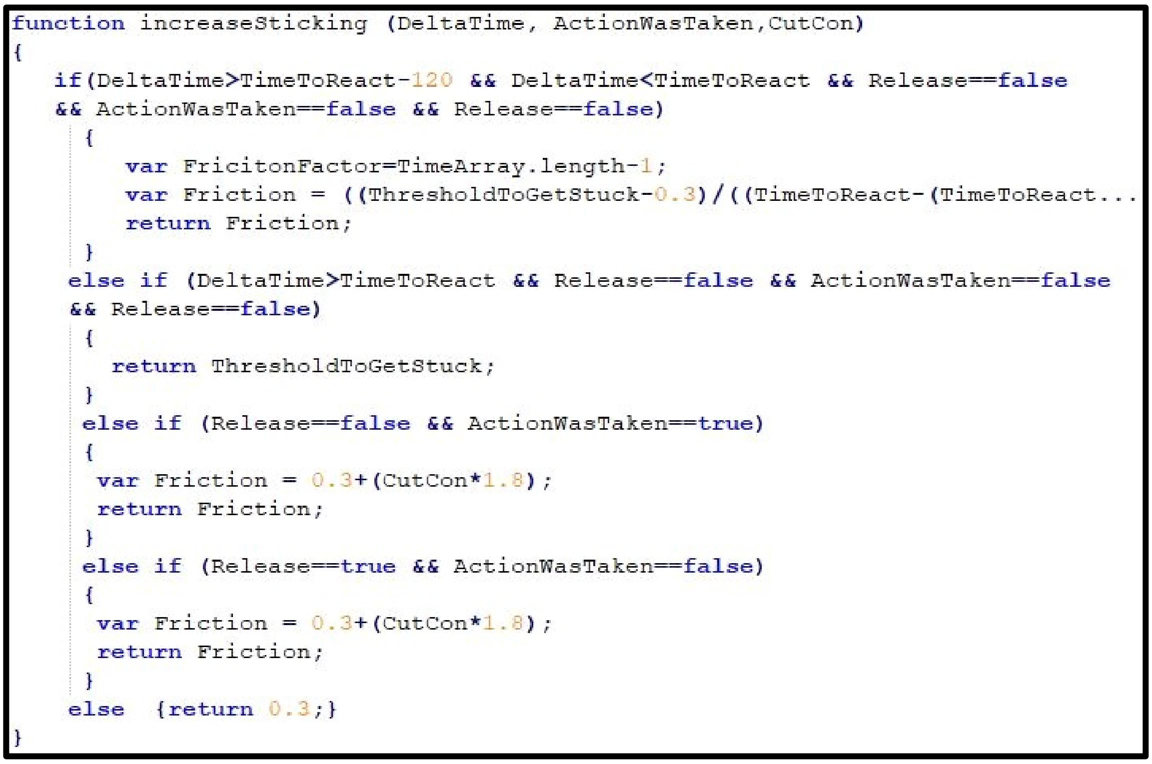
Figure 30: Time function returning the actual drilling time

Through the function illustrated in Figure 31 the increasing time causes a growth of the cuttings concentration. In case all preventive measures are executed correctly, or the freeing procedure was successfully applied, the concentration will start to decrease and to take normal values.

```
function IncreaseCuttings (CutConc, PassedTime,BitDepth, InitialDepth, ActionWasTaken, RateOfPenetration)
{
  if(PassedTime>=0 && CutConc<=maxCutConc&&ActionWasTaken==false&&Release==false
      &&RateOfPenetration>CuttingsROP_limit)
  {
    CutConc = minCutConc+((maxCutConc-minCutConc)/TimeToReact*PassedTime);
  }

  else if (PassedTime>0 && RateOfPenetration<CuttingsROP_limit && CutConc>=minCutConc
           &&ActionWasTaken==false&&Release==false&&HoldStuck==0)
    {return CutConc;}
  else if(PassedTime>0 && ActionWasTaken==true)
  {           TimeArrayCutAct.push(Date.now());
              var TimeArrayCutLengthCut=TimeArrayCutAct.length-1;
              DeltaTimeCutAct = (TimeArrayCutAct[TimeArrayCutLengthCut]-TimeArrayCutAct[0])/1000;
              CutConc = CutConc*Math.exp((-0.001*DeltaTimeCutAct));
  }
    else if(PassedTime>0 && Release==true && ActionWasTaken==false)
  {

              TimeArrayCutRel.push(Date.now());
              var TimeArrayCutLengthRel=TimeArrayCutRel.length-1;
              DeltaTimeCutRel = (TimeArrayCutRel[TimeArrayCutLengthRel]-TimeArrayCutRel[0])/1000;
              CutConc = maxCutConc*Math.exp((-0.03*DeltaTimeCutRel));
  }
    if(CutConc<minCutConc)
  {CutConc=0.14;}
  else if(CutConc>maxCutConc)
  {CutConc=maxCutConc;}
  return CutConc;
}
```

Figure 31: Function to handle the cuttings concentration

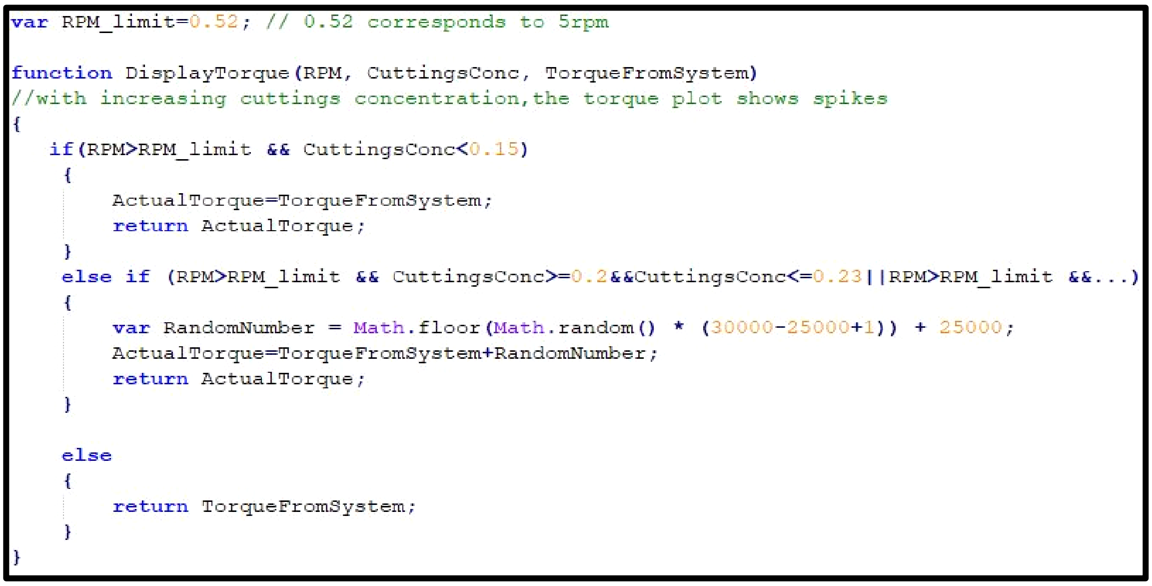
As the cuttings concentration rises, the static friction on the tag “TD.Static_friction” is turned up with the help of the function shown in Figure 32. It also causes the friction to be reduced again after the preventive or freeing actions were performed.



```
function increaseSticking (DeltaTime, ActionWasTaken,CutCon)
{
   if(DeltaTime>TimeToReact-120 && DeltaTime<TimeToReact && Release==false
   && ActionWasTaken==false && Release==false)
     {
        var FricitonFactor=TimeArray.length-1;
        var Friction = ((ThresholdToGetStuck-0.3)/((TimeToReact-(TimeToReact...
        return Friction;
     }
    else if (DeltaTime>TimeToReact && Release==false && ActionWasTaken==false
    && Release==false)
     {
       return ThresholdToGetStuck;
     }
     else if (Release==false && ActionWasTaken==true)
     {
      var Friction = 0.3+(CutCon*1.8);
      return Friction;
     }
     else if (Release==true && ActionWasTaken==false)
     {
      var Friction = 0.3+(CutCon*1.8);
      return Friction;
     }
    else  {return 0.3;}
}
```

Figure 32: Function which alters the static friction factor

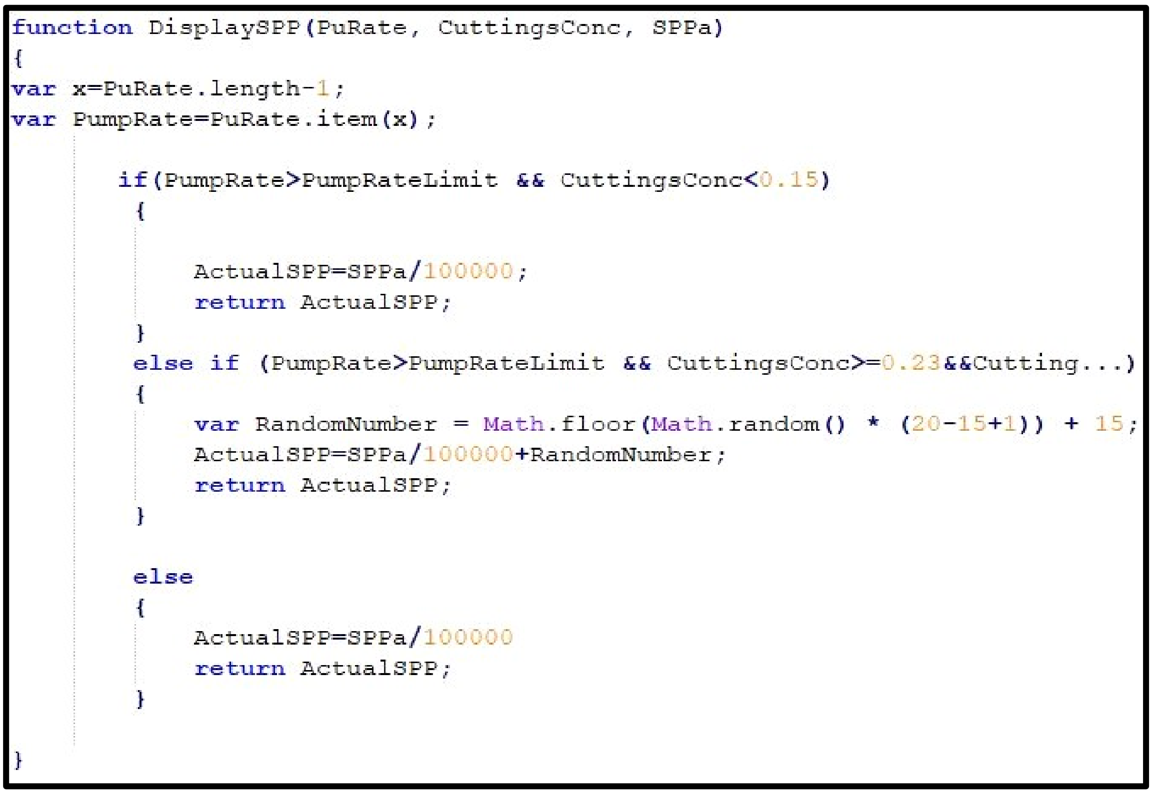
As a fluctuating torque plot is a typical warning sign of a pack-off due to poor hole cleaning, this feature was incorporated into the code, illustrated in Figure 33. This function causes torque spikes at certain cuttings concentration values and returns the normal torque values from the tag “TD.topTrqCalc” if all preventive or freeing actions were performed properly.



```
var RPM_limit=0.52; // 0.52 corresponds to 5rpm

function DisplayTorque(RPM, CuttingsConc, TorqueFromSystem)
//with increasing cuttings concentration,the torque plot shows spikes
{
   if(RPM>RPM_limit && CuttingsConc<0.15)
    {
        ActualTorque=TorqueFromSystem;
        return ActualTorque;
    }
    else if (RPM>RPM_limit && CuttingsConc>=0.2&&CuttingsConc<=0.23||RPM>RPM_limit &&...)
    {
        var RandomNumber = Math.floor(Math.random() * (30000-25000+1)) + 25000;
        ActualTorque=TorqueFromSystem+RandomNumber;
        return ActualTorque;
    }

    else
    {
        return TorqueFromSystem;
    }
}
```

Figure 33: Torque function

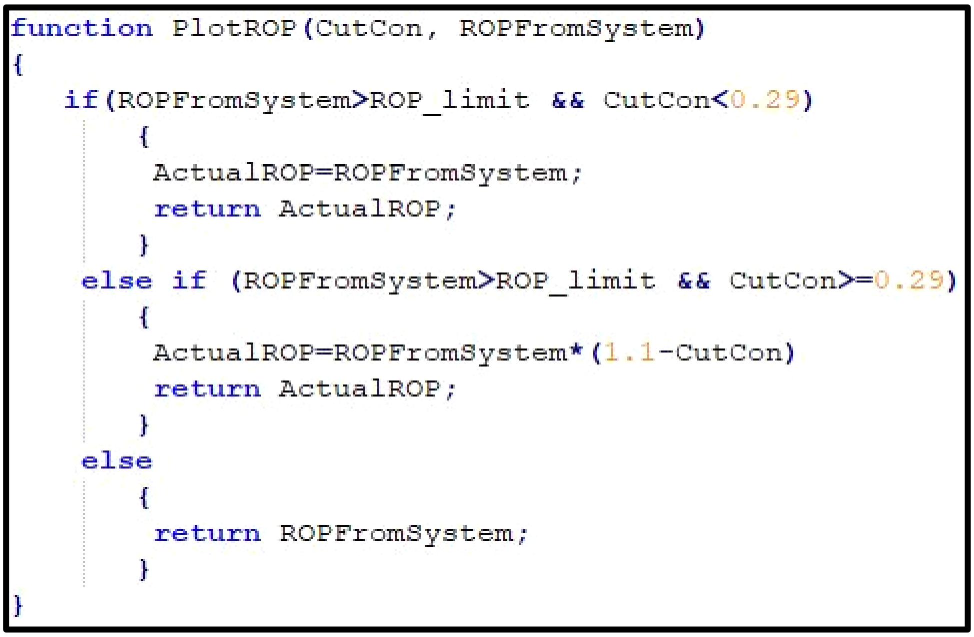
The increasing cutting concentration also causes an increasing stand pump pressure (SPP) while SPM are kept constant. By the introduction of the function shown in Figure 34 the sliding cuttings beds will produce spikes in the SPP plot.



```
function DisplaySPP(PuRate, CuttingsConc, SPPa)
{
var x=PuRate.length-1;
var PumpRate=PuRate.item(x);

       if(PumpRate>PumpRateLimit && CuttingsConc<0.15)
        {

            ActualSPP=SPPa/100000;
            return ActualSPP;
        }
        else if (PumpRate>PumpRateLimit && CuttingsConc>=0.23&&Cutting...)
        {
            var RandomNumber = Math.floor(Math.random() * (20-15+1)) + 15;
            ActualSPP=SPPa/100000+RandomNumber;
            return ActualSPP;
        }

        else
        {
            ActualSPP=SPPa/100000
            return ActualSPP;
        }

}
```

Figure 34: SPP function

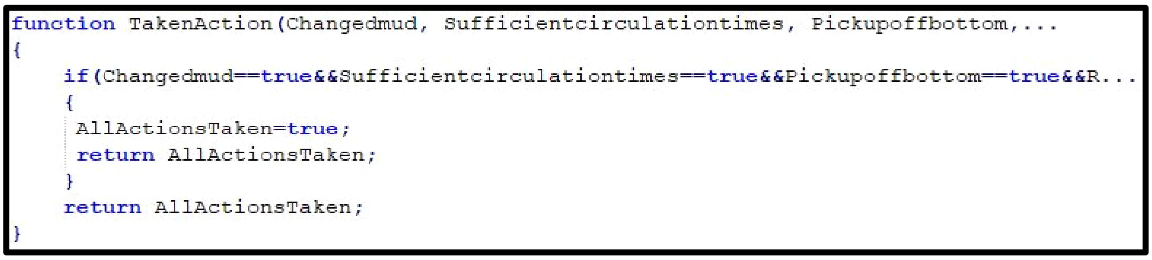
As the bottom hole pressure enlarges due to additional cuttings, the apparent rock strength increases which results in a steady decrease in ROP. This fact was incorporated in the function shown in Figure 35. When the concentration returns to normal levels, the ROP increases again.



```
function PlotROP(CutCon, ROPFromSystem)
{
    if(ROPFromSystem>ROP_limit && CutCon<0.29)
        {
         ActualROP=ROPFromSystem;
         return ActualROP;
        }
     else if (ROPFromSystem>ROP_limit && CutCon>=0.29)
        {
         ActualROP=ROPFromSystem*(1.1-CutCon)
         return ActualROP;
        }
     else
        {
         return ROPFromSystem;
        }
}
```

Figure 35: ROP function

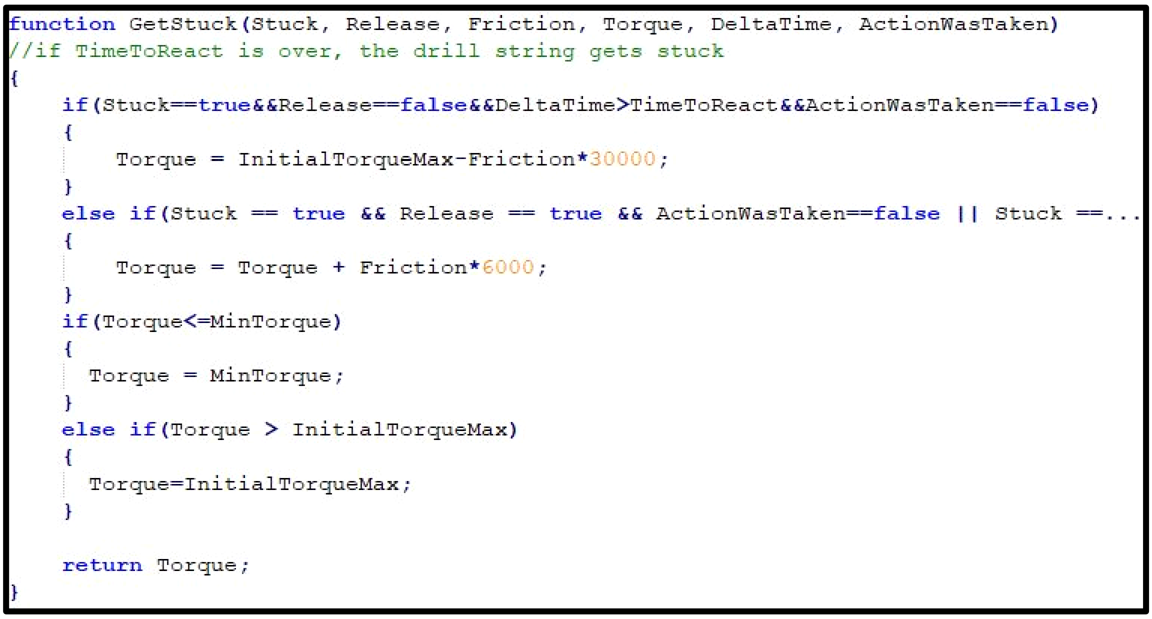
The user should recognize the pack-off warning signs produced by the functions mentioned above and set the right measures. To check if all actions are taken, the function demonstrated in Figure 36 was created. It returns either true or false and consequently causes the plots, cuttings concentration and static friction to go back to normal.



```
function TakenAction(Changedmud, Sufficientcirculationtimes, Pickupoffbottom,...
{
    if(Changedmud==true&&Sufficientcirculationtimes==true&&Pickupoffbottom==true&&R...
    {
     AllActionsTaken=true;
     return AllActionsTaken;
    }
    return AllActionsTaken;
}
```

Figure 36: Function to check if all preventive actions were taken

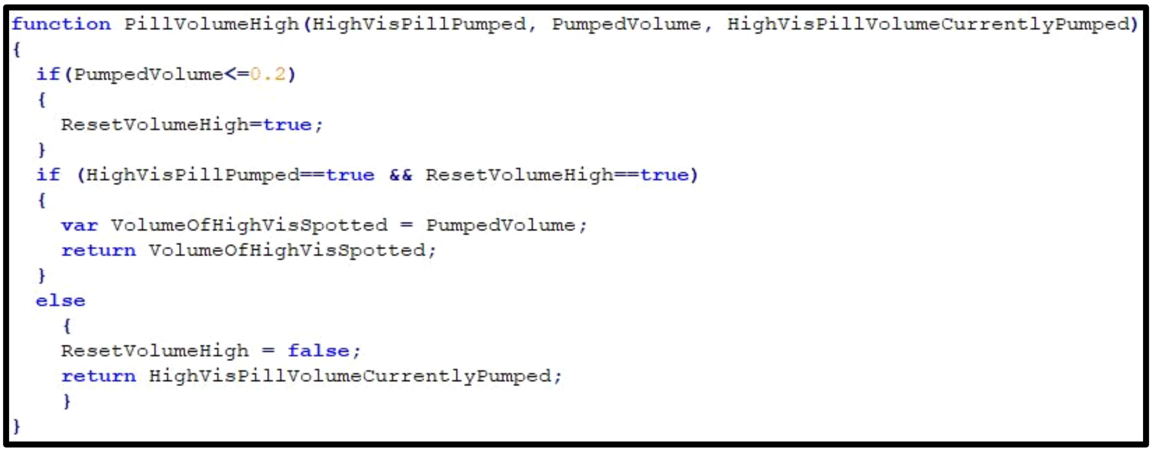
In the case that the user does not respond properly to the stuck pipe indications within a pre-defined time, the drill string gets fixed as a result of the function indicated in Figure 37. Within it, the value of the tag Worker.Torque, which corresponds to the maximum allowable torque is set to a low value. As the actual torque will always be higher than the set value, the drill string remains stuck until the freeing procedure was carried out. The correct execution of the freeing technique will affect a higher value of the Worker.Torque tag and consequently free the drill string.



```
function GetStuck(Stuck, Release, Friction, Torque, DeltaTime, ActionWasTaken)
//if TimeToReact is over, the drill string gets stuck
{
    if(Stuck==true&&Release==false&&DeltaTime>TimeToReact&&ActionWasTaken==false)
    {
        Torque = InitialTorqueMax-Friction*30000;
    }
    else if(Stuck == true && Release == true && ActionWasTaken==false || Stuck ==...
    {
        Torque = Torque + Friction*6000;
    }
    if(Torque<=MinTorque)
    {
      Torque = MinTorque;
    }
    else if(Torque > InitialTorqueMax)
    {
      Torque=InitialTorqueMax;
    }

    return Torque;
}
```

Figure 37: Function to get the drill string stuck

In order to free the pipe, the user must conduct a series of measures. As part of this procedure a certain amount of high-vis pill has to be pumped. To see the pumped volume of this pill, the function shown in Figure 38 was implemented. It also checks, if the driller has reset the pump strokes and switched from the drilling mud to the high-vis pill.



```
function PillVolumeHigh(HighVisPillPumped, PumpedVolume, HighVisPillVolumeCurrentlyPumped)
{
  if(PumpedVolume<=0.2)
  {
    ResetVolumeHigh=true;
  }
  if (HighVisPillPumped==true && ResetVolumeHigh==true)
  {
    var VolumeOfHighVisSpotted = PumpedVolume;
    return VolumeOfHighVisSpotted;
  }
  else
    {
    ResetVolumeHigh = false;
    return HighVisPillVolumeCurrentlyPumped;
    }
}
```

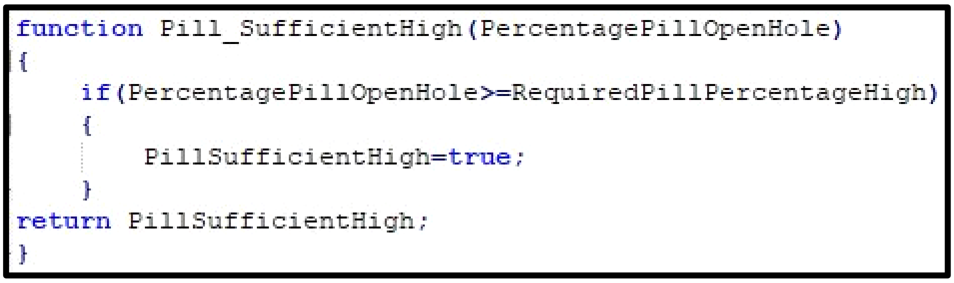
Figure 38: Function to monitor the volume of the high-vis pill

Since the high-vis pill can only fulfil its purpose when it reaches the open hole section, the function, indicated in Figure 39, was implemented to observe the percentage of the pumped pill that has reached the open hole section.

```
function PercentagePillVolHigh(ComponentID, ComponentLength, PumpedVolumeHighVis,PumpedVolum.
{
var StringIdVolume =[];
  for (var i=0; i<ComponentLength.length-1; i++)
  {
    var x=((ComponentID.item(i)*ComponentID.item(i))*3.141593/4)*ComponentLength.item(i);
    StringIdVolume.push(x);
  }
  var StringIdVolume_sum = 0;
  for (var j=0; j<StringIdVolume.length-1; j++)
     {
    StringIdVolume_sum=StringIdVolume_sum + StringIdVolume[j];
     }
    if(PillVolume>=0.1)
    {
          var PercentagePill = 0;
          var VolumeInOpenHole=PumpedVolumeHighVis-PumpedVolumeLowVis-StringIdVolume_sum;
               if(VolumeInOpenHole>0)
               {
                 PercentagePill=VolumeInOpenHole/RequiredPillVolumeHigh*100;
                       if(PercentagePill>100)
                       {
                         return 100;
                       }
                 return PercentagePill;
                }
    else {return 0;}
  }
  else {return 0;}
}
```

Figure 39: Function to observe the percentage of high-vis pill in the open hole

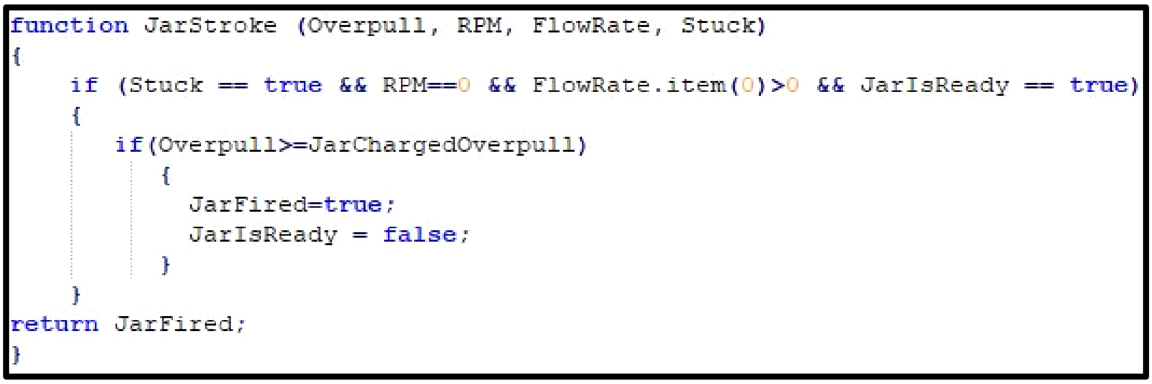
The function illustrated in Figure 40 was introduced to check if the percentage of high-vis pill in the open hole is sufficient high. In case this condition is fulfilled, it returns true.



```
function Pill_SufficientHigh(PercentagePillOpenHole)
{
    if(PercentagePillOpenHole>=RequiredPillPercentageHigh)
    {
        PillSufficientHigh=true;
    }
return PillSufficientHigh;
}
```

Figure 40: Function to verify if enough volume of high-vis pill reached the open hole

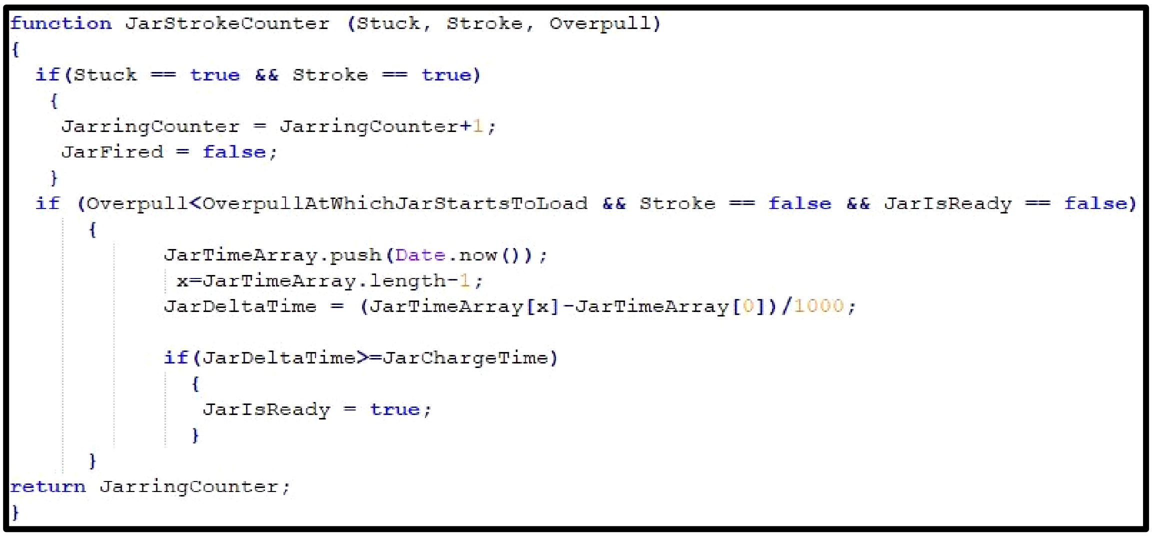
To conduct a specified amount of upward jarrings, is also part of the freeing procedure. The function shown in Figure 41 checks if the user does not apply any torque, exceeds a certain amount of overpull to fire the jar and remains circulation. If all requirements are met, the jar is fired by returning true.



```
function JarStroke (Overpull, RPM, FlowRate, Stuck)
{
    if (Stuck == true && RPM==0 && FlowRate.item(0)>0 && JarIsReady == true)
    {
       if(Overpull>=JarChargedOverpull)
          {
            JarFired=true;
            JarIsReady = false;
          }
    }
return JarFired;
}
```

Figure 41: Function to conduct the jarring operation

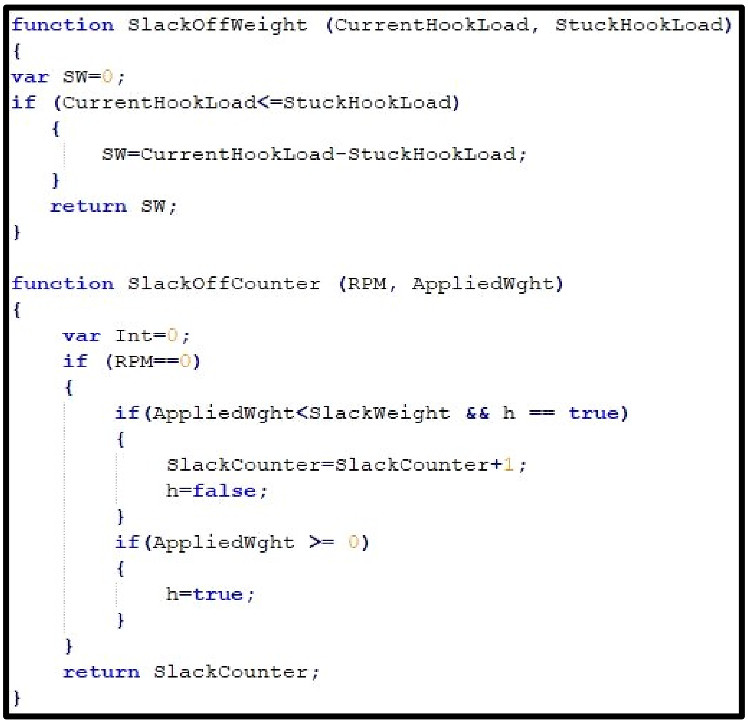
When the function depicted in Figure 41 passes true to the function indicated in Figure 42, the counter will increase the number of upward jarrings by one. After firing, this function also checks if the user has been waiting long enough below a certain overpull value to charge the jar.



```
function JarStrokeCounter (Stuck, Stroke, Overpull)
{
  if(Stuck == true && Stroke == true)
   {
    JarringCounter = JarringCounter+1;
    JarFired = false;
   }
  if (Overpull<OverpullAtWhichJarStartsToLoad && Stroke == false && JarIsReady == false)
      {
            JarTimeArray.push(Date.now());
             x=JarTimeArray.length-1;
            JarDeltaTime = (JarTimeArray[x]-JarTimeArray[0])/1000;

            if(JarDeltaTime>=JarChargeTime)
              {
               JarIsReady = true;
              }
      }
return JarringCounter;
}
```

Figure 42: Function to count the number of jarrings

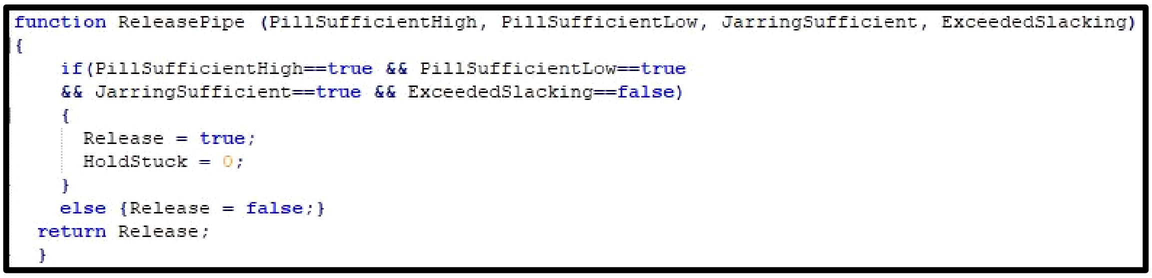
As the drill string gets stuck during drilling, the best-practice for freeing do not recommend jarring in the downward direction. As this would worsen the stuck situation, the functions shown in Figure 43 were implemented for verification. In case that the user exceeds a certain slack-off weight and thereby activates the downward directed jars, the number will be counted. If the case occurs that the user exceeds a pre-set amount of downward jars, the drill string will not be released anymore.



```
function SlackOffWeight (CurrentHookLoad, StuckHookLoad)
{
var SW=0;
if (CurrentHookLoad<=StuckHookLoad)
    {
        SW=CurrentHookLoad-StuckHookLoad;
    }
    return SW;
}

function SlackOffCounter (RPM, AppliedWght)
{
     var Int=0;
     if (RPM==0)
     {
          if(AppliedWght<SlackWeight && h == true)
          {
               SlackCounter=SlackCounter+1;
               h=false;
          }
          if(AppliedWght >= 0)
          {
               h=true;
          }
     }
     return SlackCounter;
}
```

Figure 43: Functions to account for downward jarring

Finally, the function shown in Figure 44 checks if the correct freeing procedure was executed by the user. If so, it switches the variable “Release” to true which is then handed over to the functions “IncreaseCuttings”, “increaseSticking”, “GetStuck” and the plot functions. This consequently causes the freeing of the drill string and the returning of the drilling parameters including torque, ROP, SPP, cuttings concentration and static friction factor to normal values.



```
function ReleasePipe (PillSufficientHigh, PillSufficientLow, JarringSufficient, ExceededSlacking)
{
    if(PillSufficientHigh==true && PillSufficientLow==true
    && JarringSufficient==true && ExceededSlacking==false)
    {
     Release = true;
     HoldStuck = 0;
    }
    else {Release = false;}
  return Release;
  }
```

Figure 44: Function to confirm the correct freeing procedure

In Figure 45 the most important cornerstones of the training case which have been realized by the described functions are summarized. The schematic indicates the primary things that happen during the running of the simulation.

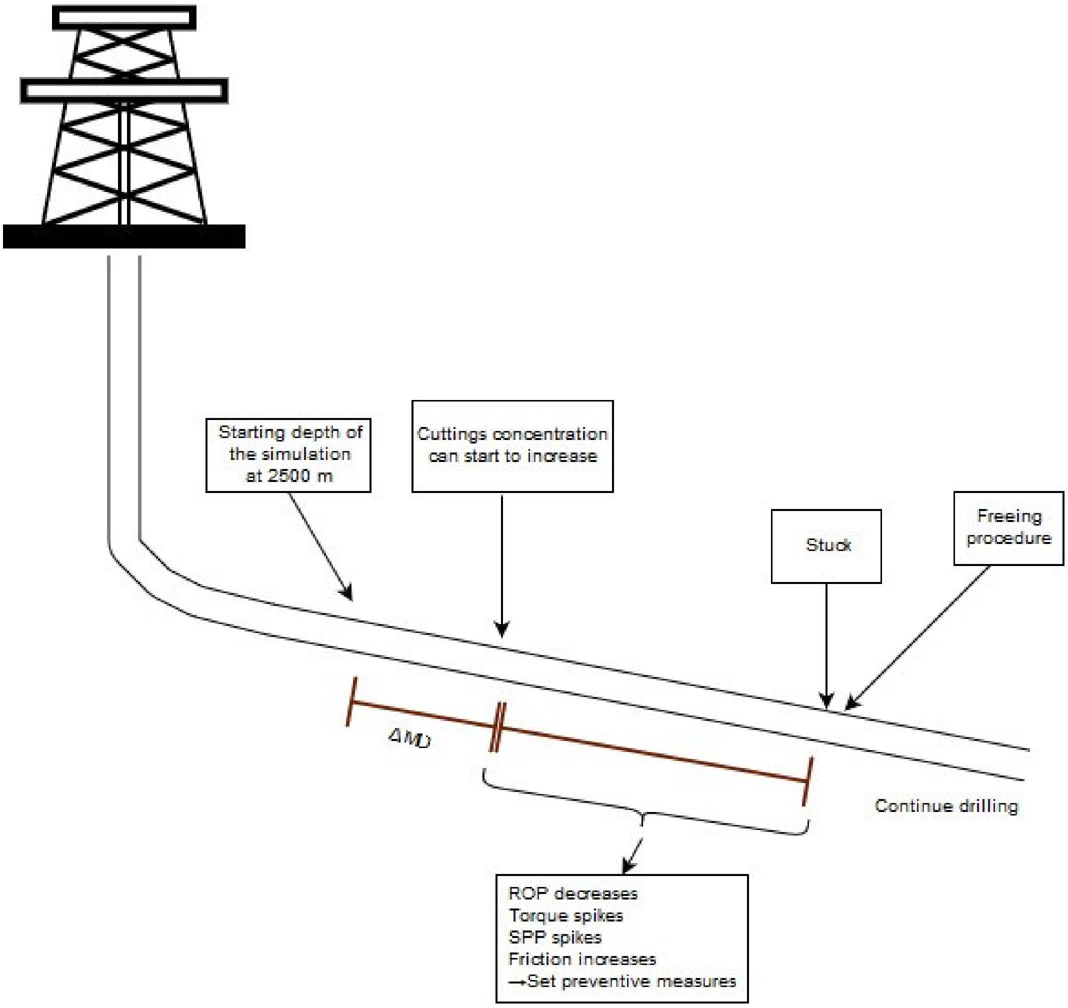


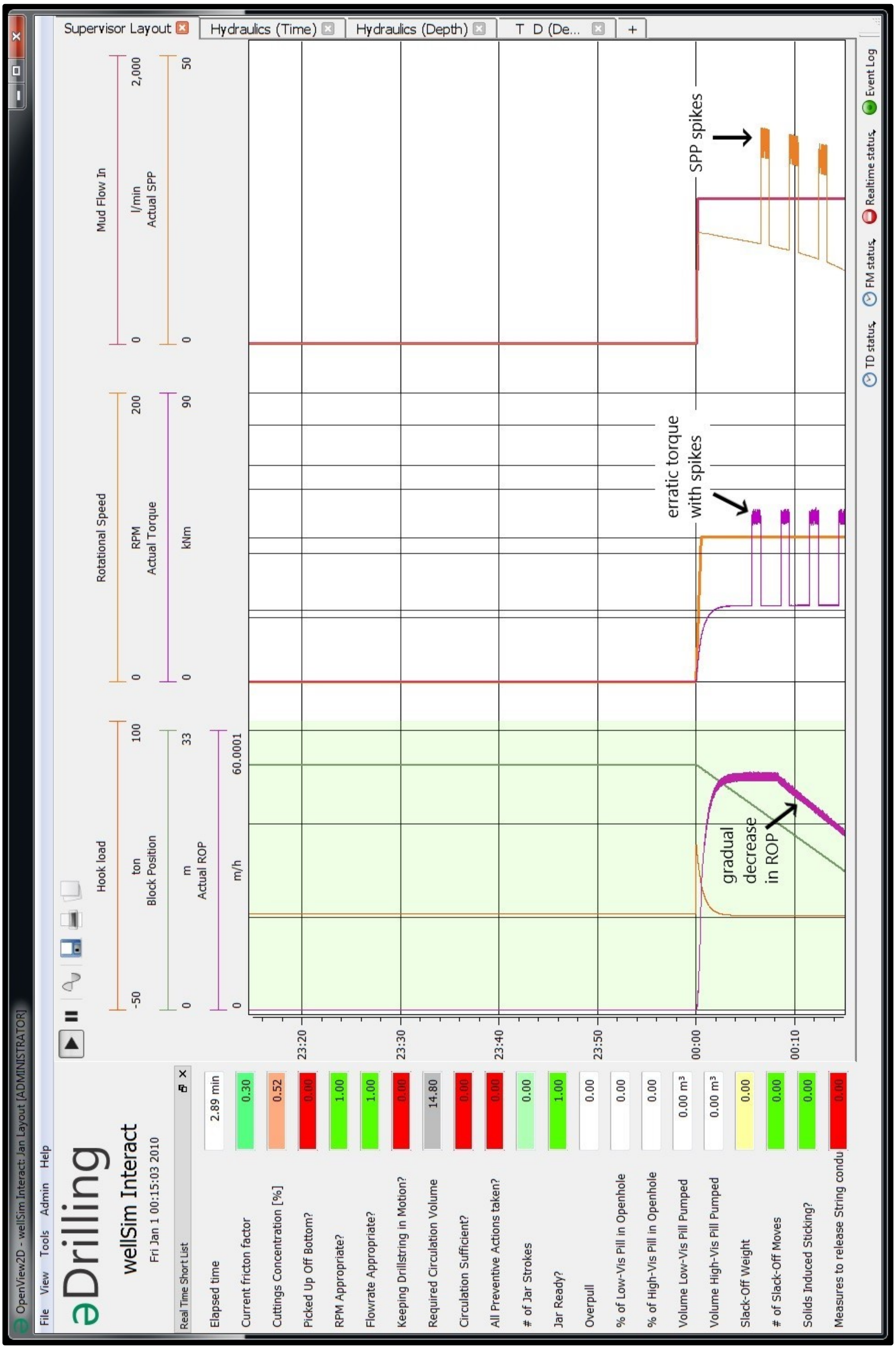
Figure 45: Schematic of the training case

4.2 Workflow of the training case

After the steps indicated in the flowchart in Table 16 are performed, the simulation can be started. The user has to click the "Play-Button" in the Drilling Control window and can set the drilling parameters[23] as desired. After a predefined depth was drilled, the cuttings concentration starts to increase. As the cuttings concentration increases with time, it causes a gradual decrease of the ROP. The resulting torque and SPP spikes which will occur due to the higher amount of cuttings are also indicative for an upcoming stuck pipe event and must be recognized by the driller. The warning signs just described are shown in Figure 46.

---

[23] RPM, Block speed and Flowrate can be controlled by the user in the Drilling Control window



gradual decrease in ROP

erratic torque with spikes

SPP spikes

Elapsed time	2.89 min
Current fricton factor	0.30
Cuttings Concentration [%]	0.52
Picked Up Off Bottom?	0.00
RPM Appropriate?	1.00
Flowrate Appropriate?	1.00
Keeping Drillstring in Motion?	0.00
Required Circulation Volume	14.80
Circulation Sufficient?	0.00
All Preventive Actions taken?	0.00
# of Jar Strokes	0.00
Jar Ready?	1.00
Overpull	0.00
% of Low-Vis Pill in Openhole	0.00
% of High-Vis Pill in Openhole	0.00
Volume Low-Vis Pill Pumped	0.00 m³
Volume High-Vis Pill Pumped	0.00 m³
Slack-Off Weight	0.00
# of Slack-Off Moves	0.00
Solids Induced Sticking?	0.00
Measures to release String condu	0.00

Figure 46: Indications to react upon

After these symptoms become visible, the time to react upon the indications starts to count. The time to react on these warning signs can be chosen arbitrary by typing it in seconds next to the variable "TimeToReact in the calculate.js file. In order to prevent the drill string of becoming stuck, the following measures[24] must be carried out within the allowed time:

- Pick-up off bottom for at least half a meter
- The rotational speed must be maintained between 65 and 135RPM as it improves hole cleaning
- To avoid washouts in unconsolidated formations, the drills string must be kept in motion either up or down between 30m/h and 40m/h
- In order to suspend more cuttings, the user must switch to the mud with higher PV and YP
- Rest the pumped volume to monitor the amount of new mud
- The flowrate has to be set between 700-1300l/min
- Circulate until the volume exceeds the inside volume of the drill string plus two times the annular volume of the open hole section. This can be verified by observing the box "Required Circulation Volume" in the "Real Time Short List" on the left of the OpenView2D window, indicated in Figure 46, and the amount of pumped fluid in the "Drilling Control" interface. To shorten the pumping time, it is recommended to accelerate the simulation by using the buttons "x1 x2 x5 x10" in the "Drilling Control" window.

After the user has performed all these steps, the box "All Preventive Actions taken?" turns green. The cuttings concentration and friction will start to decrease. Consequently, the torque, SPP and ROP plot will normalize and the user can proceed with the simulation without troubles.

In case that the trainee overlooks the pack-off indications, the static friction factor is raised in the last 60 seconds of the allowed reaction time. When the friction factor reaches the value of 10, the string gets stuck. The RPM drops to zero in the Drilling Control window, and if it is tried to reciprocate the string by adjusting the block speed, the bit depth will remain the same. The user now has to execute the following measures to become free again:

- The first step is to set the rotational speed to zero
- Since the scenario is in a horizontal section, it is essential to pump a low-vis pill first in order to disturb the cuttings. This is done by switching the fluid to the low-vis pill.
- Afterwards, it is essential to reset the number of strokes to monitor the pumped volume as it is included in the code
- Spot 0,3m^3 of low-vis pill
- Next, the disturbed cuttings must be suspended and brought out of the well. This is achieved by switching to the high-vis pill
- It must not be forgot to reset the strokes to monitor the pumped volume
- Pump 0,3m^3 of high-vis pill

---

[24] The values to be achieved can be changed as desired in the calculate.js file

- Then the fluid can be switched back to the normal drilling mud
- The next step is to pump the pills down until they have reached the BHA. This is reached after pumping approximately 13,5m^3, which is the inside volume of the drill string, of mud down the well. By use of the boxes "% of Low-Vis Pill in Openhole" and "% of High-Vis Pill in Openhole" in the "Real Time Short List" on the left side of the OpenView2D window this condition can be verified, see Figure 46. The usage of the buttons "x1 x2 x5 x10" in the "Drilling Control" panel will shorten the time to pump the pills down the drill string.
- While pumping the pills and waiting until they have reached the BHA, the jarring operation can be commenced. It must be ensured that no torque is applied by setting the rotational speed to zero. As torsional and tensile stresses are additive, jarring upwards during torque application is not recommended as it would damage the drill string. The user must jar three times in the upward direction. As with real operations, a certain value has to be exceeded in order to fire the jar. This is done by pulling the string upwards and exceeding the overpull value of 4000kg. After firing, the jar needs to be reset. For the up-jarring, the driller must slack-off[25] to recharge the jar. In this scenario, the jar is recharged by reducing the overpull below 400kg. After 30 seconds below this value, the jar is ready and can be fired again.
- The user must be careful to not apply more than -4000kg on the drill string, as this would fire the jar in the downward direction. As the drill string got stuck during drilling, this would worsen the situation and reduce the chance of freeing. If the user fires the downward jar more than one time, the releasing of the stuck string will be prevented.

In case all these actions are performed, the cuttings concentration goes back to normal which also causes the normalization of the friction and the displayed plots. The drilling operation can be continued without any further stuck pipe issues due to solids.

Table 20 shows the entire workflow of the training case. It includes the values of the parameters to be set and describes all steps and measures to be performed. It should be noted that the workflow is only valid if all modifiable parameters are left at their default values.

---

[25] Apply weight

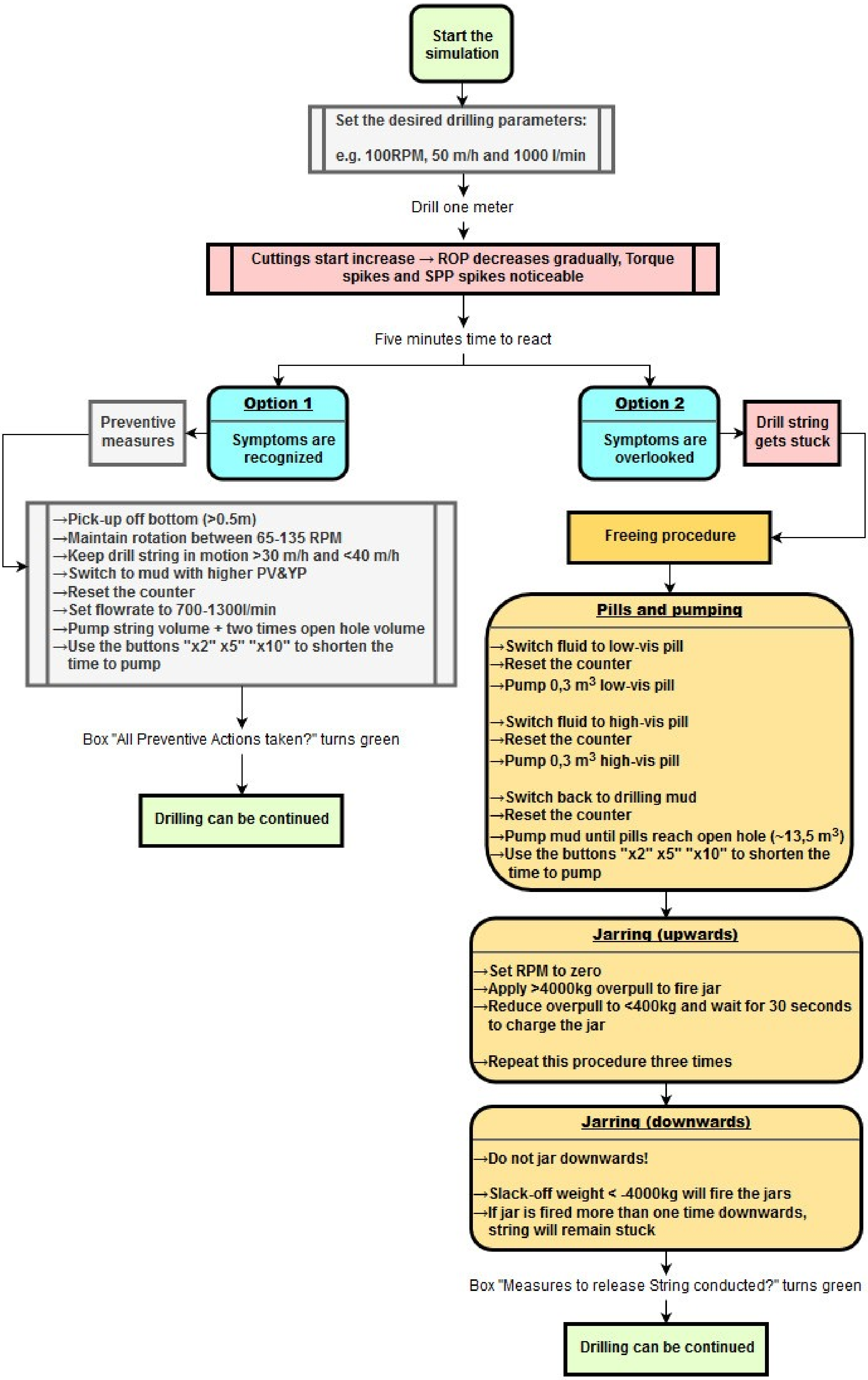


Table 20: Workflow of the training scenario

4.2.1 Values that can be changed as required within the training case

Prior to the running of the developed training scenario, a lot of variables can be set as desired. When opening the calculate.js file, all pre-defined parameters can be found at the beginning of the code. Table 21 summarizes these factors and describes their meaning. After the explanation, the default value of the respective parameter is given in brackets.

DeltaMD	The MD in meter that must be drilled before the cuttings concentration can start to increase (1)
ThresholdToGetStuck	Threshold for the friction that causes the pipe to get stuck (10)
TimeToReact	Time in seconds given to the user to respond to the symptoms (300)
minCutConc	Minimum cuttings concentration (0,07)
maxCutConc	Maximum cuttings concentration that is used as a threshold to cause sticking (0,85)
RequiredBUCirculations	Required amount of bottom-up circulation for the open hole section (2)
RequiredPickUpOffbottom	Distance needed to be counted as pick-up off bottom (0,5m)
maxRPM	Maximum allowable RPM during the preventive measures (10,47); 1RPM corresponds to 0,1047
maxFlowrate	Maximum allowable Flowrate during the preventive measures (0.015); 1l/min corresponds to 0.000015
RequiredJarrings	Number of required upward jarrings to release the drill string (3)
JarChargeTime	required time in seconds to recharge the jars (30)
OverpullAtWhichJarStartsToLoad	Overpull in kg below which the upward jar starts to recharge (400)
JarChargedOverpull	At this overpull value the upward jar is fired (4000)
RequiredPillVolumeLow	Needed volume of low-vis pill in m^3 (0,3)
RequiredPillVolumeHigh	Needed volume of high-vis pill in m^3 (0,3)

RequiredPillPercentageLow	Percentage of low-vis pill that must have reached the open hole in order to release the drill string (85)
RequiredPillPercentageHigh	Percentage of high-vis pill that must have reached the open hole in order to release the drill string (85)
SlackWeight	Slack-off value in kg at which the downward jar is fired (-4000)
TimesSlackOff	If this quantity of downward jarrings is exceeded it is impossible to free the string (2)

Table 21: Changeable variables

Chapter 5 Conclusion and future work

Solids induced stuck pipe events implicate enormous costs and are exceptionally time-consuming. However, the occurrence of this problem can be recognized by specific indications long before this issue becomes crucial. Therefore, it is important to instruct operational personnel and engineers about the right behaviour in this situation. The developed training case on the eDrilling AS simulator provides a unique method to train the ability to identify and properly react to characteristic symptoms. In this way, the occurrence of stuck pipe can be avoided, and the NPT reduced, leading to an efficiency improvement of future drilling operations.

The literature shows common best practices for solids induced stuck pipe prevention which overlay with the opinions from experts. The training case incorporates those best practices and teaches them in an interactive way. In combination with the workflow which encompasses the essential preventive actions and freeing procedures to successfully complete the training scenario, it can assist in turning trainees into highly qualified junior staff.

The provided system files have proven to be highly useful to add additional code and increase the functionality of the software package. The elaborated training case clearly shows the potential for further development and can be therefore seen as a concept for further and more complex scenarios on the drilling simulator. The handbook which covers each implementation step of the created training case facilitates and accelerates the enlargement of the training portfolio.

During the elaboration of the scenario, it was found that the eDrilling simulator can serve as a unique tool for the operational staff of tomorrow to gain experience and knowledge for real procedures. Though it must be admitted that the system shows some weaknesses if utilized as a design tool. Additionally, further improvement of the computational stability is highly recommended as the system frequently crashes during simulations. These advancements must be undertaken by eDrilling to enhance the user-friendliness of the system. Despite the limitations, further research is needed to confirm the progressive impact of this novel training instrument on the behaviour during real drilling operations. The investigation of this attempt is well suggested to be a topic for another thesis.

Acronyms

BHA	Bottom hole assembly
ECD	Equivalent circulating density
ESD	Equivalent static density
HCR	Hole cleaning ratio
LGS	Low gravity solids
MBT	Methylene blue test
MTV	Minimum transport velocity
NPT	Non-productive time
PDC	Polycrystalline diamond compact
POOH	Pull out of hole
PV	Plastic viscosity
PWD	Pressure while drilling
RKB	Rotary kelly bushing
ROP	Rate of penetration
RPM	Revolutions per minute
SPM	Strokes per minute
SPP	Stand pipe pressure
URL	Uniform resource locator
YP	Yield point

Symbols

m	mass	[kg]
$''$	inch	[in]
n	flow behaviour index	[-]
N	Newton	[kg*m/s^2]

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