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Cuttings Transport Modeling - Part 1: Specification of Benchmark Parameters with a Norwegian Continental Shelf Perspective

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Abstract

In oil and gas drilling, cuttings transport related problems are a major contributor to well downtime and costs. As a result, solutions to these problems have been extensively researched over the years, both experimentally and through simulation. Numerous review articles exist, summarizing not only the research history but also the qualitative effect of individual case parameters such as e.g. pump flow rate, pipe rotation, rate of penetration on cuttings transport. However, comparing different studies is challenging, as there is no common reference basis defined in the form of typical and representative set of case parameters.

In order to develop relevant and accurate cutting transport models, it is critical that both experiments and models are targeting flow cases, which are relevant for respective drilling operations. By developing a clear understanding of the industrial parameter space, as well as establishing critical benchmarks, the development of models and corresponding laboratory experiments will become much easier.

Other industries have established such benchmarks (e.g. the "NREL offshore 5-MW baseline wind turbine" in wind power research), providing a standardized set of case parameters and profiles, readily available for use to researchers worldwide and resulting in straightforward benchmark and validation as well as faster project set-up and definition.

For application to modeling of cuttings transport phenomena, we propose a methodology how to derive a well-defined and standardized set of geometrical, operational, and environmental case parameters describing various working points of actual drilling operations and procedures as well as simplified problems. The relevance and application of standard parameters is briefly discussed in the light of modeling, both experimentally and through simulations.

Introduction

The study of hole cleaning has been a major concern for several decades in the drilling industry. Inadequate hole cleaning can lead to stuck pipe, fractured formation, high rotational torque, premature bit wear, decreased ROP, and further cause problems during logging, casing, and cementing operations. It was reported that 70% of the time lost with unexpected events in drilling was associated with stuck pipe (Massie et al., 1995) and one third of the stuck pipe problems were due to inadequate hole cleaning (Hopkins et al., 1995).

The problem of cuttings transport in vertical wells has been well studied. For directional drilling, managing cuttings is more challenging, and a better understanding of cuttings transport processes is required to achieve a more accurate prediction of cuttings concentration and distribution.
Wellbore inclination can significantly influence cuttings transport efficiency. During drilling, rate of buildup of cuttings concentration in the wellbore changes gradually as the inclination angle increases up to 30° (Tomren, 1979; Iyoho, 1980). For angles over 30°, particles may settle at the low side of the annulus and significant changes may occur in cuttings-fluid flow patterns, where cuttings dunes or beds may build up. The cuttings beds or dunes formed at inclination angles between 30-60° are not stable, and may tumble downward whenever the annular flow is shut down, also known as cuttings avalanches. Variations in cuttings moving patterns and unstable beds or dunes make 30-60° inclinations the most difficult region for cuttings transport in deviated wells. Hole cleaning for intermediate inclined wells is particularly difficult because of the dramatic change of flow configurations and the tendency of cuttings to slide downward. Inadequate hole cleaning for wells in this range of inclination angles can lead to a series of drilling problems.
Cuttings transport problems are one of the major contributors of well downtime. In order to avoid cuttings build-up in the wellbore the drilling industry in general and drilling engineers in particular have an interest in increasing cuttings transport knowledge, including real-time (RT) models to help in monitoring, decision making and optimization. RT hole cleaning models (Cayeux et al., 2016, 2013) have demonstrated that the transport of cuttings depends on the local conditions along the borehole (hole geometry, inclination, fluid velocity, drill pipe rotational speed) and cuttings particles transport is governed by two key mechanisms: advection of particles in suspension and rate of cuttings bed erosion, i.e. the lifting of particles into suspension from a formed cuttings bed.
One of the most important reasons for the complexity of cuttings transport is that it is affected by many parameters by a varying degree, some of them unmeasurable or even not fully known. The most critical parameters are fluid flow rate, density and rheology, wellbore geometry and inclination, drill pipe eccentricity, drill pipe rotational speed, and cuttings density and morphology (Adari et al., 2000). A generic set of parameters has been formulated with the focus on oil drilling in general (Nazari et al., 2010). A dedicated case parameter description with value ranges has been established for coiled tubing (CT), based on previously published studies (Kelessidis et al., 2002).

Types of drilling operations & scenarios

Drilling on the Norwegian Continental Shelf (NCS) offers drilling an array of well profiles ranging from vertical, directional, side-tracks and extended reach profiles. But generalizing drilling operations and scenarios is very often not possible since hole cleaning problems are case and field sensitive. Thus, various hole cleaning practices exist with regard to the specific drilling operations such as conventional, directional, liner, high-pressure/high-temperature (HP/HT), extended reach, deep water, CT and aerated drilling. For deep water and liner drilling; controlling of ECD is challenging while maintaining a circulation sufficient for a clean-hole. HP/HT wells, by definition, require a higher density fluid which typically requires high solids loading and imposes extra challenges on cuttings transport and ROP. In many circumstances, hole cleaning is more efficient if a low-viscosity fluid is pumped in turbulent flow rather than a high-viscosity fluid in laminar flow. The major differences between conventional rotational drilling and CT drilling are the absence of pipe rotation and the continuous circulation of drilling fluids (Leising et al., 2002). For a typical CT drilling job, the challenge is achieving the circulation rate required to keep the hole clean.

During operations, several challenges pertaining to hole cleaning are encountered while making connections, tripping-in, tripping-out and drilling ahead. Existing operational guidelines are for instance:

- During tripping-in and tripping-out operations, the hole should be circulated until shakers are clean. Should the drag increase gradually while running in hole (RIH) or pulling out of hole

(POOH), the string should be reciprocated with low rotation and circulate minimum 3-4 bottoms up in order to try to mechanically wipe out cuttings beds (ENGIE, 2013).
- Prior to making connections while RIH, circulate the hole at the planned section flowrate in order to evacuate cuttings surrounding the bottomhole assembly (BHA). After making the connection, pump rates should be brought up in steps prior to continuing drilling (ENGIE, 2013).
- During drilling ahead, poor hole cleaning symptoms are abnormally low cuttings discharge, large amount of fill after trips, high pick up weights, poor drillstring weight transfer, stuck pipe, high ECD, high torque and drag, reduced penetration rate, difficulty in running casing and packing off (Mims and Krepp, 2007). In vertical sections cuttings transport is optimized by increasing mud viscosity, maintaining a high YP, high gel strength, high YP/PV ratio, using viscous sweeps and maintain laminar flow (Mims and Krepp, 2007). In horizontal sections, maintaining turbulent flows and low viscosities is considered best for cuttings transport (Cayeux et al., 2014).

Types of research methods

Various research methods have been used in cuttings transport research. Here we distinguish between laboratory experiments (modeling the well on a laboratory scale with physical experiments) and virtual models (virtual experiments/simulations on computing hardware) such as RT/mechanistic models, or various types of physics-based, multi-dimensional models such as Computational Fluid Dynamics (CFD).

A conceptual overview of the logical relationships of different type of research methods and the real drilling process is provided in Figure 1. RT models, as well as mechanistic and 1D models, predict *wellbore*[1] states (in RT). Vice versa they can to a certain extent be validated with RT data for a particular wellbore. Thus, RT models have to be fed with input data, and they require a parameter set describing the relevant case parameters of the problem along with numerical values of these (configuration data).

Cuttings transport studies, however, usually investigate a small element of the wellbore, a *wellbore subsection*[2]. A laboratory model uses an annular geometry with the length being approximately three orders of magnitude smaller than the wellbore. Through experiments on this level one may study effects relevant for cuttings transport directly. Ideally, data from laboratory experiments is combined with 3D CFD modeling to gain a better understanding of the process. Based on such understanding, improvements to mechanistic models for RT applications may be made.

Virtual models on the *wellbore subsection* level again require a case parameter set in order to provide a solution. This set of parameters has to equally serve as a specification for the laboratory model in order to validate simulation with laboratory results.

Correct interpretation what is going on in different parts of the well in terms of cuttings transport based on simulations and measurable data is the end-goal.

Experimental/laboratory

Experiments are usually carried out on laboratory scales to study solid-liquid problems. Experimental results may be used to develop models for predicting the flow behavior in the annulus, including the volumetric flowrate required to avoid cuttings beds in inclined wellbores. In order to analyze the flow, measurements of flow conditions such as e.g. temperature and pressure are required. To enable use of advanced measurement and visualization techniques one usually needs to use translucent drilling fluid substitutes. High time-resolution optical measurements are needed to capture transient phenomena,

[1] *Wellbore* refers to the whole wellbore and takes a holistic view on the process (Adari et al., 2000).
[2] *Wellbore subsection* refers to an annular element downhole (with a length in the order of one drill pipe element or less) and is equivalent to the domain of interest in experimental or CFD cuttings studies.

including visualization of flow patterns and measurement of velocity profiles. Also, fast pressure transducers are needed to measure fluctuating pressure gradients in the annulus.

Real-Time/1D/Mechanistic

The main purpose of RT drilling process models is to support decision making on the rig "up to the point of automatic control of the drilling machinery" (Florence and Iversen, 2010). Thus, these models need to deliver solutions in real-time with a certain accuracy. Today, RT models feature a high complexity with regards to different details of the drilling process (Florence and Iversen, 2010). They usually address more dynamics than just cuttings transport, i.e. drillstring mechanics and vibrations, and temperature. Several flow patterns may occur in annular wellbore flows depending on the operational conditions. This makes it difficult to identify one mechanistic model which can cover all relevant flow patterns. Hence, various mechanistic models are used with respect to different flow patterns. However, as opposed to CFD models, RT models usually are 1D with regard to multiphase flow and cuttings transport calculations. The cross-sectional area of the annulus is not fully resolved, but modeled with a certain amount of layers representing the different phases and fields, i.e. bed and drilling mud. The model equations get increasingly complex the more physical effects are considered. Furthermore, an increasing number and complexity of sub-models, closures and correlations is required in order to adequately model all effects of interest in RT.

CFD (RANS & DNS)

CFD can be used to investigate a 3D fluid problem and obtain a 3D solution, providing pressure and velocity fields. Balance equations for mass, momentum and (depending on the assumptions/required solution) energy are solved numerically on a three-dimensional grid of the domain of interest. If a second phase, such as dispersed particles/cuttings, is part of the problem this can be either treated as a second continuum (Eulerian-Eulerian concept) or as individual particles (Eulerian-Lagrangian method). In the latter case more computational effort arises as the particles trajectories are computed for each particle.

Mainly depending on the available computational power and the desired accuracy of the result the following concepts can be distinguished:

- Direct Numerical Simulations (DNS) resolve turbulence on on all length and time scales down to the Kolmogorov length and time scale.
- Large Eddy Simulations (LES) resolve turbulence on length and time scales larger than gridsize and time step (→ resolving "Large Eddies") and modeling turbulence on subgrid scales.
- Reynolds-Averaged Navier-Stokes (RANS) approaches entirely model the effect of turbulence on all length and time scales. The respective turbulence model is chosen with regards to the physics of the problem.

The latter method is generally being used for CFD cuttings transport modeling purposes as less computational power is required.

Problem description & scope of this paper

Comparison between different hole cleaning study results is challenging, as chosen case parameters can have different values. In order to study the various mechanisms and processes influencing hole cleaning, studies are usually performed on simplified cases, and as a result limit the set of case parameters defining the problem. It seems, that there is no common set of case parameters applied in the drilling industry when it comes to hole cleaning research. As a result, it is difficult to comparing existing experimental and simulation studies (Table 1) in order to quantify the effect of individual parameters and therefore mainly qualitative statements are made in review papers (Table 1).

The aim of this paper is to suggest a well-defined and standardized set of geometrical, operational and environmental case parameters describing selected drilling operations and procedures as well as simplified problems which can contribute to increased alignment in research within the field of cuttings transport. A simple methodology is presented providing benchmarks/case parameter sets for both the entire *wellbore* and for a *wellbore subsection*. Standard parameters related to cuttings transport are suggested as an example and discussed with regards to their application in modeling, both experimentally and through simulation.

Methodology

Developing parameter sets for different drilling operations and procedures conceptually follows the red arrows indicated in Figure 1. An overview of this methodology is provided in this section and illustrated with a particular example afterwards. Additional parameters relevant for virtual modeling such as CFD and experimental modeling are briefly presented.

Derivation of case parameter sets for cuttings transport problems

Parameter sets for cuttings transport studies are derived based on a specific drilling operation and drilling procedure. A particular set of such parameters defines a particular problem or case. Figure 2 depicts a conceptual overview of the proposed methodology. Once a drilling operation and procedure is defined one can in general identify the relevant parameters determining the problem along with according characteristic ranges for these parameters. The first level of Figure 2 addresses the *wellbore* as a whole, whereas the second level focusses on a particular *wellbore subsection*. Again, a list of parameters together with numerical values is required to describe the problem on this level. When investigating a particular problem, one usually studies specific working points of the system of interest. Each working point is represented by a list of case parameters, with only one numerical value per parameter (or a profile if the problem is transient), the sum of all working point parameter lists are usually termed as test matrix.

We consider the complete description of a particular problem as depicted in Figure 2 a *use case*[3] for, in our case, cuttings transport studies by either experimental or virtual modeling.

Parameter space for cuttings transport problems

The parameter space of a cuttings transport problem can be visualized as depicted in Figure 3. Main dimensions shown are sections - generally correlating with depth, total vertical depth (TVD) and/or measured depth (MD) - and sections currently drilled in - generally corresponding with time - as well as all other relevant parameters. The red space in Figure 3 encompasses the full wellbore at all times and consequently all sections and depths drilled in. By defining a specific section of interest, e.g. the 8.5" section as the section currently drilled in, one can refine the parameter space. However, the spatial focus is still the *wellbore*. In order to yield a parameter space relevant for cuttings transport studies conducted in a laboratory or using CFD, a redefinition of this parameter space is required in such a way that it describes a particular *wellbore subsection* instead. It should here be noted that we can only define our parameter ranges as current characteristic ranges. Drilling methodologies and materials, including drilling fluids, are under continuous development. For example, there has been a historic development from simple vertical wells to deviated wells to extended reach wells going continuously longer and deeper with increasing temperatures and pressures. Such development continuously extends the parameter ranges describing the drilling process.

[3] In software and systems engineering, a use case is a description of interactions between an actor and a system to achieve a goal. A use case, in our context, is a full description of a physical system/process that is to be modeled.

Wellbore

For simplicity, we exemplify with *conventional* drilling considering two scenarios: quasi-steady-state *drilling ahead* and a transient *pump start up* scenario. For the first scenario a parameter space of a generic cuttings transport problem has already been presented (Nazari et al., 2010) using an abstract system/process view on drilling and cuttings transport. Parameters and variables are classified as inputs, internal states or outputs.

We propose to elaborate on this concept as follows and presented in Figure 4:

- **Mud rheology** is to be expressed by constitutive equations with coefficients or tabulated data. We here use a simple Bingham model as it allows us to easily exploit aggregated well data available from the Norwegian Petroleum Directorate (NPD). Top hole rheology is the input, true effective mud rheology (mainly as a function of local pressure and temperature (Maglione et al., 2000) is an internal state.
- All **hole angles** and **hole sizes** for different wellbore sections are to be specified. Ideally, this information is related to a given trajectory.
- **Lithology** needs to be expressed by various parameters relevant to cuttings transport, at least rock type, density, porosity and bottomhole temperature.
- **Cutting size** is to be specified in more detail by cuttings sizes and ideally a respective size distribution.
- **Eccentricity** is to be described by two normalized spatial coordinates (Cartesian coordinate system, i.e. e_x and e_y or cylindrical coordinate system, i.e e_R and e_θ) instead of one as it describes the position of the drillstring in a two-dimensional space (Menand et al., 2006). Ideally, this information is related to a given trajectory.
- **Hookload** is not considered to be an input parameter. We rather think of it as an internal state since block position and/or the speed of the drill string seem to be the manipulating input variables. Furthermore, we cannot relate it to a specific parameter used in experimental or virtual cuttings transport modeling on the wellbore subsection level.

The parameters of lithology, cuttings size and eccentricity are unknown in actual drilling operations, and prognoses and estimates are made for modeling of drilling operations.

The relevance of individual parameters for hole cleaning varies as indicated in Figure 4 with numbers in parenthesis, e.g. mud flow rate is the most influential one (Adari et al., 2000). Input parameters are not interrelated. For example, selection of mud type and rheology is a function of the formation drilled.

The elaborated concept depicted in Figure 4 defines the relevant parameters and corresponds to the first level of both Figure 1 and Figure 2 as well as the specific section of interest in Figure 3. Thus, the scope of this approach is to handle the complete *wellbore*. Unfortunately, the parameters do not directly apply to any specific *wellbore subsection*. Clearly specified local parameters are needed in order to investigate cuttings transport both using experimental and virtual models.

Wellbore subsection

When applying the elaborated concept depicted in Figure 4 to a certain *wellbore subsection* in order to model cuttings transport in 3D (corresponds to the second level of Figure 1 and Figure 2 as well as the particular *wellbore subsection* in Figure 3), one needs to re-define the input vector of parameters as illustrated in Figure 5. What is an internal state of the previous problem formulation becomes an input and has to be specified, i.e. eccentricity, cuttings sizes, and effective apparent rheology. Some of the outputs of the previous level, i.e. ROP, consecutively become an input. Additional parameters appear as a replacement for previous ones such as e.g. the cuttings flow rate. The length of the domain of interest has to be specified as well. New internal states arise such as e.g. 3D velocity and pressure fields, cuttings bed height, and turbulent kinetic energy.

After having established parametric ranges for the scope of the *wellbore*, one needs to derive values for the inputs stated in Figure 5 in order to describe a particular *wellbore subsection*. As they are unknown, well informed estimates are made from field data (Mims and Krepp, 2007; Murchison, 2001) or, if available, results from a RT/1D/mech. model (i.e. drillstring deformation) of the previous problem formulation may be exploited.

Research method specific parameters

Various additional parameters have to be considered and specified depending on the applied method of research.

Laboratory experiments

Experiments on well hydraulics and cuttings transport should aim to simulate the drilling conditions as close as possible. Both the annular and pipe geometry, fluid and particle properties as well as dynamics of the experiments should be defined based on best choice of scaling laws and well flow parameters mentioned in Figure 4 for the *wellbore* and Figure 5 for the *wellbore subsection*. In order to develop universal models for a wide range of drilling conditions, dimensionless parameters should be developed based on the Buckingham Pi theorem. However, scaling experiments with non-Newtonian fluids is challenging. Due to the non-linear flow characteristics of these fluids, exact scaling of such problems is in general not possible. Furthermore, many dimensionless parameters may arise from the Buckingham Pi analysis, which mutually oppose each other while attempting to downscale the model. Due to limitations on the possible parameters values, these might even come in mutual conflict when attempting downscaling. Therefore, a selection of dimensionless parameters is required based on our best physical understanding. The use of scaling methods will help in achieving a scenario that is as close as possible to real well conditions. Provided we are able to understand and model such scaled processes, the same models should also be adaptable to actual drilling conditions.

With this information, measurement devices such as e.g. flow meters, differential pressure cells, thermometers, and densitometers as well as components such as pumps, separators and heat exchangers may be selected to control the flow conditions and fluid rheology in the flow loop. The pipes can be transparent for low-pressure flow loops allowing for visual observation. Non-intrusive measurement techniques may then be used, such as e.g. Laser Doppler Anemometry (LDA), Particle Image Velocimetry (PIV), and Ultrasonic Velocity Profiling (UVP), to measure the instantaneous velocity field. UVP techniques have the advantage of being applicable for both low and high pressures and even non-transparent pipes and fluids, provided adapters for good acoustic transmission are used.

Depending on the particular experimental setup, additional parameters such as type, position, accuracy and calibration of measurement devices and components arise.

Real-Time/Mechanistic/1D

The real time or 1D flow models will have parameter sets very similar to the CFD models. In general, 1D models are mechanistic, but rely heavily on simplified closure models which can be tuned to experiments or to on-line operational data. Such closure models enable solving of the problems, but may, in some cases, violate basic principles such as mass or energy conservation. Typical additional parameters, required for 1D modeling but not for CFD, are those relevant to system behavior; correct prediction of pressure waves, prediction of avalanches of cuttings, methods to handle complex rheology and the applied methods for laminar, transitional and turbulent flows. We note that, in case of commercial simulators, some of the methods applied may be trade secrets and not specified. This is of course a parameter by itself.

CFD

Generally additional parameters induced by CFD models vary with the particular approach applied. As an example, turbulence may be modeled by DNS, LES, or RANS. In the latter case one has to select a particular turbulence model suited to the problem and specify the respective model parameters. Furthermore, the resolution of the boundary layer (fully resolved vs. modeled with wall functions) will add more parameters. Discretizing the domain with a mesh will result in parameters such as cell type, number of cells and boundary layer refinement. Depending on the flow pattern (amongst other parameters such as e.g. available computational power), a multiphase modeling approach (Eulerian-Eulerian vs. Eulerian-Lagrangian) has to be chosen. Within this selection, a particular model (i.e. Two Fluid, Drift-Flux, in the first case and DEM, DPM, in the latter case) with associated parameters is to be used. Boundary conditions (BC) add further parameters as do the numerical procedures needed to solve the system of equations.

Results

Following the proposed methodology as described in the previous section, an example of parameter specification is provided for the selected case of a *drilling ahead* scenario in *conventional* drilling. Two parameter sets are generated, one for the *wellbore* and one for a *wellbore subsection*. The latter is further compared with parameter sets of recent cuttings transport studies. The section concludes with examples of relevant use cases for modeling purposes.

Example of case parameter sets

In order to provide a numerical example for the formulated methodology, we focus on a *drilling ahead* procedure in a *conventional drilling* operation, apply a regional focus on the NCS and limit ourselves to water-based muds (WBM). For the *wellbore* scope the 8.5" section is defined as the section currently drilled according to Figure 3. For the *wellbore subsection* scope we focus on the 8.5" section specifically.

Wellbore

By exploiting publicly available exploration and appraisal wellbore statistics for the NCS ("FactPages of NPD," 2015) and correlating data with MD the following information is obtained as summarized in Table 2:

- A general **MD_{MSL}** range of 450-8000 m is estimated for wells incorporating a 8.5" section, according to Figure 6. However, a distribution analysis (Figure 7) reveals that the interval 1500-4500 m covers 94% of all 8.5" sections.
- **Bottomhole temperature** range is estimated approximately to 50-150°C with regards to the specified conventional drilling operation and exclusion of HT operations according to Figure 8.
- The **PV** range is estimated to 10-60 mPa·s. Figure 9 shows PV correlated with MD. Most PVs seem to lie in the range of 10-40 mPa·s. However, a distribution analyis of the above defined depth range (Figure 10) shows that an interval of 10-60 mPa·s encompasses 95% of the distribution.
- The **YP** range is estimated to 0-20 Pa. Figure 11 shows YP correlated with MD and indicates two value ranges, one with YP = 0 (Newtonian fluid behavior) and one with YPs ranging from approximately 5-20 Pa. A distribution analysis of the above defined depth range according to Figure 12 shows that an interval of 0-20 Pa encompasses 95% of the distribution and that for the considered depth range less Newtonian fluids with a YP = 0 are used (45 % vs. 36%).
- **Mud density** is estimated to 1000-1800 kg/m³ (corresponding to 1.0-1.8 g/cm³). Figure 13 shows mud density correlated with MD and indicates a trend to higher mud weights for deeper depths as well as an increasing distribution with deeper depth. A distribution analysis of the above defined depth range according to Figure 14 shows that an interval of 1000-1800 kg/m³, corresponding to 1.0-1.8 g/cm³, encompasses 96% of the distribution.

Since no further data is available to exploit, we make the following educated guesses for the remaining parameters:

- The desirable **mud flow rate** range for effective hole cleaning is specified as 1700-2300 lpm, the range of 1325-1515 lpm is considered the minimum for effective hole cleaning (Mims and Krepp, 2007)[4].
- The desirable **rotational speed** range of the drill pipe for effective hole cleaning is 70-100 rpm, 60 rpm is considered the minimum rotational speed for effective hole cleaning (Mims and Krepp, 2007).
- **Drill pipe sizes** typically used on the NCS to drill 8.5" sections are usually 5" and 5.5".
- In recent times, typically PDC **bit types** have been used on most runs while drilling the 8.5" sections on the NCS.
- **Hole angles** range from 0° to 90° since all inclinations can generally occur in a well. However, depending on the particular well profile/trajectory, not all sections will feature all inclinations. For instance the 42"/ 32" and 26" / 24" are typically drilled vertically on most wells in the NCS.
- **Rock types** are specified as Limestone, Sandstone and Clay as these are the main formations on the NCS. Due to lack of data we use textbook values (Fjaer, 2008; Schön, 1996) in order to estimate the characteristic ranges of the rocks density and porosity as indicated in Table 2.

Wellbore subsection

We choose to primarily work with the 8.5" section for specifying meaningful parameter value ranges for a *wellbore subsection*. Value ranges are specified using Rules-of-thumb as follows and summarized in Table 3:

- **ROP** is estimated to range from 5 m/hr to 30 m/hr for normal operating conditions. There exist concepts such as an empirical equation for drillability (Mitchell and Miska, 2011, p. 80) or ROP models (Warren, 1987). However, we use the experience from drilling operations, as at this point we are primarily concerned with a typical range.
- **Cuttings flow rate** may be estimated based on mass conservation (Bourgoyne Jr et al., 1986, p. 57)

  $$\dot{V}_{Cut} = \frac{\pi(1-\phi)d^2}{4} ROP \quad \text{.....[1]}$$

  where ϕ is rock porosity, d is bit/hole diameter, and ROP is Rate of Penetration. Assuming ROP and porosity ranges as indicated in Table 3, the range of potential cuttings flow rates is estimated to 5-18 lpm for the 8.5" section.
- **Eccentricity** of the drill pipe ranges from 0 to 1 in the radial and 0 to 360° in the circumferential direction. Generally all eccentricities may occur due to well trajectory and deformation of the drillstring (Menand et al., 2006).
- **Effective mud rheology** is known to be a complex function of well temperature, pressure and shear rate as well as mud formulation and structure (Maglione et al., 2000). Mud rheology will be largely affected by the mostly unknown mud temperature downhole which depends on heat transfer to the mud. Thus, the effective mud rheology (described in a simplified manner by PV & YP in this paper) will generally change with temperature. In most cases the drilling mud becomes less viscous the deeper and by that warmer it gets (Maglione et al., 2000; Santoyo et al., 2001; White et al., 1997). Bentonite and KCL based WBM systems used on the NCS seem to also show

[4] In case of a transient pump start up scenario a profile is to be specified. Typically, one would start at 0 lpm and ramp up to a specified flow rate in a certain period of time, with two stops during the ramp. The first stop is performed in order to check for return flow, the second is to check for activation of Measurement While Drilling (MWD).

this behavior (Torsvik et al., 2014). However, we choose to not apply any changes to the values describing the *wellbore* scope as indicated in Table 2 when transferring to the *wellbore subsection* scope as indicated by Table 3 since changes in effective viscosity apparently occur in the same order of magnitude. Furthermore, there apparently are examples were the effective viscosity actually increases with depth and temperature (Santoyo et al., 2001) due to other effects not considered here, such as pressure.

- The **length** of the subsection of interest represents the length of the annular geometry used for modeling purposes. We consider it to be an open parameter as it depends on the length scales of the phenomena to be modeled, e.g. dune movement vs. velocity profile. On the other hand it is restricted by available computational power and/or laboratory space.
- **Cuttings size** is a major unknown. It is dependent on formation type, area drilled, bit type, amongst others. Cuttings size and irregularity will also typically be reduced from one *wellbore subsection* to another as the cuttings are subjected to the mechanical forces of the drillstring and shearing/collision with each other. Accessibility of cuttings size data is limited. For this reason, we are only able to state a generic interval of 0.007-40 mm for shale formations based on previous studies (Rye, 2005; Saasen et al., 2013)[5].

All other parameter ranges remain the same due to lack of more detailed information.

Comparison with recent cuttings transport studies

A comparison of the established parameter sets with those of some arbitrarily selected recent cuttings transport studies is provided in this section.

Table 5 shows the parameter sets of three CFD cuttings transport studies (Akhshik et al., 2015; Dykes, 2014; Al-Kayiem et al., 2010) with the corresponding experimental studies used for model validation (Osgouei, 2010; Sanchez et al., 1999; Tomren et al., 1986) as well as the parameter sets of one experimental study (Taghipour et al., 2013).

Parameters directly specifying the particular cuttings transport problems are not always fully disclosed. In one case, a cuttings flow rate is not provided (Akhshik et al., 2015)[6], while in another case neither ROP nor cuttings flow rate is provided (Akhshik et al., 2015)[7]. The mud density is not disclosed in three studies (Akhshik et al., 2015; Dykes, 2014; Taghipour et al., 2013). However, in case of the simulation papers (Akhshik et al., 2015; Dykes, 2014) the values for cuttings flow rate, ROP and mud density can be obtained from the corresponding experimental papers (Sanchez et al., 1999; Tomren et al., 1986). Depth and temperature are only stated once in respectively (Al-Kayiem et al., 2010) and (Taghipour et al., 2013) and no paper provides a value for porosity. Some studies state cuttings mass flow rate (Al-Kayiem et al., 2010) or fluid velocity (Akhshik et al., 2015; Dykes, 2014) instead of volume flow rates[8]. In terms of rheology a direct comparison is not straightforward since different rheology models are used[9]. Additionally, informative parameters such as hole depth, temperature and porosity are not provided in some cases. Some studies (Akhshik et al., 2015; Taghipour et al., 2013) state velocities instead of mud flow rates[8].

[5] A PSD of cuttings of an exploration well in the Barents Sea (no formation/section provided) indicates a range of 0.007-7 mm (Saga, 1994 in Rye, 2005). A more recent study (Saasen et al., 2013) established PSD of top-hole NCS drill cuttings based on data for two different wells (36", 26", 17.5", 12.25" sections). For a 36" section in sand formation cuttings between 0.02 and 2 mm were found. For 26", 17.5", 12.25" sections in shale formation cuttings between 0.02 and 20 mm were found, with a trend towards finer grains for deeper sections. Up to 40 mm cuttings were observed visually.

[6] The value provided in Table 5 has been calculated using equation [1] assuming a porosity of zero.

[7] The value provided in Table 5 has been obtained using the corresponding experimental paper.

[8] Values provided in Table 5 have been converted to volume flow rates using density or the annular cross-sectional area.

[9] We have obtained PV & YP from power-law (Taghipour et al., 2013; Al-Kayiem et al., 2010; Tomren et al., 1986) or Herschel-Bulkey (Akhshik et al., 2015) model coefficients based on API definitions (American Petroleum Institute, 2010).

The parameter values of the referenced studies are in some cases representing our derived ranges, i.e. hole angles, eccentricity, ROP and rotational speed, mud and cuttings density. However, in other cases (mud flow rate, rheology, cuttings flow rate, geometry) the values of the referenced studies are smaller than our derived ranges. For instance, in terms of cuttings flow rate, only one study lies in our proposed range (Sanchez et al., 1999), while all the other feature lower flow rates than our flow interval. However, all of them apparently use the mass conservation concept based on equation [1] in order to determine a cuttings flow rate. All referenced studies have used either water or, in terms of density, fluids similar to water.

Use cases

Finally we present different use cases for the purpose of modeling cuttings transport problems. All are based on the examples provided in the previous section.

A selection of defined use cases with regards to different levels of (modeling) complexity is depicted in Figure 17. In order to build more sophisticated models aggregated from simpler ones, the presented use cases are designed to address the multi-facetted problem of cuttings transport with increased complexity. Thus, some of the use cases do not directly correspond to a cuttings transport problem in drilling but rather serve as an intermediate step towards more sophisticated models, i.e. "…in Pipe" and "(1) Plain mud". We distinguish between "steady" and "unsteady" problems with regards to the operational drilling parameters (e.g. a mud flow rate of 1500 lpm vs. a mud flow rate profile of 0 to 1500 lpm with a flow rate gradient increase of 10 lpm every second[10]). Presumably, rheology models used in virtual modeling may have to be more sophisticated for the "unsteady" problems, as drilling muds are time-dependent fluids in general.

We also distinguish between complex geometries and kinematic boundary conditions, such as flow in an annulus with a rotating drillstring, and simple geometries such as plain mud flow in a drill pipe.

For "steady" problems, the simplest case is pure Non-Newtonian pipe flow of plain mud (single phase flow, no cuttings) which corresponds to flow through the drill pipe in our defined *wellbore subsection* (1). A more complex case is an annular geometry. Again, two levels of complexity can be investigated: Plain mud (1) and mud with dispersed cuttings (2), which correspond to a successfully flushed *wellbore subsection* and a flushing procedure respectively. The third level of complexity is the *drilling ahead* scenario as described in Table 3. Again, we distinguish between with (2) and without cuttings (1) corresponding to continuous *drilling ahead* and a flushing procedure respectively. The very same levels of spatial and single phase/multiphase complexity are valid when investigating an "unsteady" problem such as the mentioned *pump start-up* procedure. But as opposed to the *drilling ahead* case, in a *pump start-up* procedure only an initial cuttings bed might be present, no cuttings are generated and pipe rotation is zero.

Table 4 provides example parameter sets for some of the use cases presented in Figure 17. The numerical values are partly chosen arbitrarily within the characteristic range indicated in Table 3.

Discussion

The proposed methodology allows a specification of a set of parameters for a *wellbore subsection*. This is not straightforward as in some cases a direct link between a tophole parameter such as hookload and a corresponding bottomhole parameter cannot be established. However, it is shown that a set of parameters describing a *wellbore* tophole are not sufficient to describe a specific *wellbore subsection* since the list of parameters are not equivalent. Internal states and outputs of the *wellbore* description become inputs for the *wellbore subsection*.

[10] The terms "steady" and "unsteady" refer to the input parameters and not to the internal states and/or outputs. In case of turbulence and dispersed cuttings, the solution (internal states, outputs) will always be transient/unsteady.

Case parameter sets

Numerical value ranges for both the *wellbore* and *wellbore subsection* scope are determined by exploiting aggregated wellbore data of the NPD.

Having more sophisticated (consistent and comprehensive) aggregated data would potentially yield a more precise value range for respective parameters and drilling operations and procedures. The numerical values provided for the individual parameter sets are based on various assumptions using partly inaccurate or insufficient data. The establishment of characteristic parameter value ranges is for instance purely based on MD due to lack of accessible TVD cases. Mud rheologies and densities as well as casing & section data are only available with regards to MD. This could be avoided if more sophisticated data was available, including both TVD and MD for respective parameters. However, the error seems to be small since most wells in the exploration database feature a fairly low MD/TVD ratio (Figure 15), indicating that in most cases MD is fairly close to TVD.

The obtained characteristic ranges per parameter are based on various simplifying assumptions, mainly limited with respect to accessibility of data. Particular examples are:

- **Operation** - We have focused on conventional drilling. This complies only to some extent with the data we have used. Extended-reach operations (MD/TVD > 2) do not seem to be part of the data as indicated by Figure 15. The cases of HP/HT operations, however, were excluded on the basis of bottomhole temperature (< 150 °C) only, as the data does not contain any information about downhole pressure.
- **Inclination** - We have not distinguished between vertical, intermediate and highly inclined wells since the majority of wells in the exploited exploration database are fairly vertical (Figure 16). By including the development well database one could potentially gain a more specific picture with regards to well inclinations.
- **Temperature** - In case of bottomhole temperature we have not distinguished between different geological sections of the NCS. It seems more appropriate to divide the NCS into different sectors and establish a respective temperature relationship as indicated in Figure 8.
- **Rock properties** - By categorizing the NCS into different sectors, it is possible to narrow down rock properties, i.e. cuttings density and porosity.
- **Mud type** - The subset of data used does not fully represent all WBM cases due to data quality. The available data does incorporate a mixture of mud categories, brand names as well as no information with regards to mud types. We have only considered data where the mud type is clearly identifiable as WBM.
- **Mud rheology** - We have based our parameter specification on PV & YP, which is equivalent to the Bingham rheology model. In order to provide a range of relevant rheologies, the Bingham model may be sufficient. However, PV & YP are generally insufficient to provide an appropriate picture of mud rheology and are in particular not suited for modeling purposes due to the inaccuracy of the model (Hemphill et al., 1993). Though one can obtain corresponding power-law (PL) or Herschel-Bulkey (HB) model coefficients from PV & YP, e.g. through API definitions (American Petroleum Institute, 2010), this is inconclusive, as for a certain rheology expressed with purely PV and YP there exist more than only one potential set of PL and HB coefficients. Ideally, a more sophisticated rheology model such as i.e. the Unified Herschel-Bulkley model (Mario Zamora and David Power, 2002) is used.
- **Hookload** is considered as an internal state and block position and/or the speed of the drill string are considered input variables on the wellbore level. Further investigation seems required how these input parameters and internal states relate to a specific parameter used in experimental or virtual cuttings transport modeling on the wellbore subsection level and how they exactly affect cuttings generation and build up or vice versa.

The actual availability of (aggregated) data is an issue, as highlighted above. Furthermore, replication of hole cleaning for a particular well with RT models requires RT data (upper level of Figure 1). In case of long directional wells, the accuracy of directional measurements may be poor. Data for cuttings properties and flowrates are not normally available. Drilling fluid measurements are usually accessed through the drilling data report of the operator or the drilling fluid report of mud supplier, and are not normally streamed in real-time, although there is a current focus on automation of such systems (Iversen and Geehan, 2015).

The case parameter value ranges established in this study are based on normal operational data. In order to pinpoint the most critical case parameter configurations, a cuttings transport problem data base may prove beneficial. Similar to the NPD factpages, but only containing problematic (in the sense of hole cleaning) case parameters referenced to real cuttings transport incidents.

Comparison with recent cuttings transport studies

The benchmarked studies feature parameter values which are only partly within our derived intervals.

None of them have worked with the exact same geometry as we have used to derive our parameter sets. However, most studies have used very similar hydraulic diameters (0.079, 0.089 m). As mentioned above, in some cases rheology is not directly comparable, due to different models used. It seems reasonable, that, despite a common hydraulic diameter, other values are not coinciding with our intervals since the general purpose is to investigate cuttings transport problems. In that sense a mud flow rate lower than our specified interval seems of higher interest. Interestingly, many studies have used a fairly moderate ROP and therefore a lower cuttings flow rate as we have estimated. The cuttings mass flow rate is mainly based on equation [1]; however, the effect of porosity seems not to be considered. Another aspect is mud density being generally on the very low end of our derived characteristic range. This may be due to laboratory restrictions, such as laboratory fluids being mainly based on water without any weighting additive.

It should be noted that the numerical values used in this paper are particular examples. The actual values mainly depend on initial assumptions as well as choices made when specifying a use case. Other parameter sets, such as the examples referenced in this paper, are just as valid. However, due to vast differences in parameter values, only a qualitative meta-analysis of these studies could be conducted. It is necessary to transfer one set of parameters to another in order to compare results and conduct a quantitative meta-analysis. This requires a scaling concept based on all relevant parameters and on our best physical understanding. Besides, laboratory or computational constraints may impose limitations to the parameter range, which requires a scaling of the problem. Apparently, very few cuttings transport studies actually seem to have non-dimensionalised the respective problem of interest (Kelessidis et al., 2002; Li and Walker, 2001; Luo et al., 1992; Ozbayoglu et al., 2007), all of which have made use of a Newtonian viscosity.

Use cases

The use cases presented in this paper represent a very small subset of all potential use cases. In fact, the amount of uses cases seems endless, given the amount of parameters, their characteristic ranges, drilling operations and procedures, and associated simplified problems. Referring to a particular drilling operation and procedure enables one to determine characteristic parameter ranges and establish specific use cases. All use cases presented are specified with regards to a laboratory scale, which in the provided example is equal to the *wellbore subsection* scale. However, this is not necessarily always the case. For instance, one might not be able to work with the very same spatial dimensions (annular and pipe diameter, length) and/or temperatures. In such cases, an adequate scaling concept is required to scale down the defined *wellbore subsection* parameter ranges to a laboratory setup if needed.

Benchmarks

We would like to emphasize that the drilling industry could gain both efficiency and effectiveness if standard parameter sets for modeling purposes were available to researchers. This is the case in other industries such as wind power research (Jonkman et al., 2009), which provide a standardized set of case parameters and profiles readily available for use to researchers worldwide. In CFD modeling there also exists standard test cases such as e.g. the Sod shock tube problem (Sod, 1978) for code verification and benchmarking of results.

In this paper we provide a simplified example of how case parameter sets for cuttings transport research can be established. If established on a more generic and sophisticated basis (addressing different drilling operations and procedures, regions, well profiles, mud types and based on more accurate aggregated data, i.e. the above mentioned cuttings transport problem data base) and combined with case sets of experimental and drilling data, benchmarks might help improve effectiveness and efficiency in wellbore transport research:

- **Effectiveness**: Since the benchmarks/parameter sets would cover the industry's mainly used and most challenging operating points with respect to cuttings transport, the industrially relevant problem in terms of absolute numbers would be investigated in each study.
- **Efficiency**: Since the benchmarks/parameter sets would be available to the research community upfront a faster start-up of new projects as well as straightforward benchmarking and validation of results could be performed.

Conclusion

This paper presents parameter sets and use cases along with specified parameters with a focus on the NCS. Use cases with case parameter sets presented may serve as a reference for experimental and virtual modelers in a cuttings transport research project to help ensure consistent work throughout the project. Across the project, these parameter sets are considered to serve as benchmarks in order to standardize research efforts.

The parameters summarized in Figure 5/Table 3 are regarded essential when specifying any cuttings transport problem and their numerical values should be fully and comprehensively disclosed in any publication. Additional research-method dependent parameters, as briefly described in section *Research method specific parameters*, should also be fully disclosed in order to enable repetition of the study. Furthermore, it might be of value to additionally provide the most important non-dimensional numbers characterizing the investigated problem, i.e. Reynolds number, Particle Reynolds number, Stokes number. For some of these various definitions exist, especially with respect to non-Newtonian rheology, in which case the applied definition should also be provided.

Further development of benchmarks as suggested in this paper should make use of both a comprehensive and a more sophisticated rheology model. Studies should ideally disclose rheology data in addition to model coefficients due to the diversity of mud rheologies used in drilling.

A holistic scaling concept, based on physically sound non-dimensional numbers, which is incorporating all parameters relevant to cuttings transport and accounts non-Newtonian rheology seems required.

Further research in order to clarify the effect of hook load on cuttings transport (or vice versa) and the dependence of wellbore subsection parameters on hook load (or vice versa) seems necessary.

The development of a database containing critical parameter sets of the industries most relevant cuttings transport problems, together with respective experimental and/or field data seems very beneficial for further hole cleaning research. The drilling industry could gain both efficiency and effectiveness if standard parameter sets for modeling purposes were available to researchers as this would result in focusing on the industry's mainly used and most challenging operating points as well as a faster project start-up and straightforward comparison and validation of results.

Nomenclature

1D = One Dimensional
3D = Three Dimensional
BC = Boundary Conditions
CFD = Computational Fluid Dynamic
CT = Coiled Tubing
DEM = Discrete Element Method
DNS = Direct Numerical Simulation
DPM = Dispersed Phase Model / Discrete Particle Method
ECD = Equivalent Circulating Density
HB = Herschel-Bulkley
HP/HT = High-Pressure/High-Temperature
LDA = Laser Doppler Anemometry
LES = Large Eddy Simulation
MD = Measured Depth
MWD = Measurement While Drilling
MSL = Mean Sea Level
NCS = Norwegian Continental Shelf
NPD = Norwegian Petroleum Directorate
PIV = Particle Image Velocimetry
PDC = Polycrystalline Diamond Compact drill bit
PL = Power Law
POOH = Pulling Out Of Hole
PV = Plastic Viscosity
RANS = Reynolds-Averaged-Navier-Stokes
RIH = Running In Hole
RoP = Rate of Penetration
RT = Real-Time
TVD = Total Vertical Depth
UVP = Ultrasonic Velocity Profiling
WBM = Water-Based Mud
YP = Yield Point

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Figures

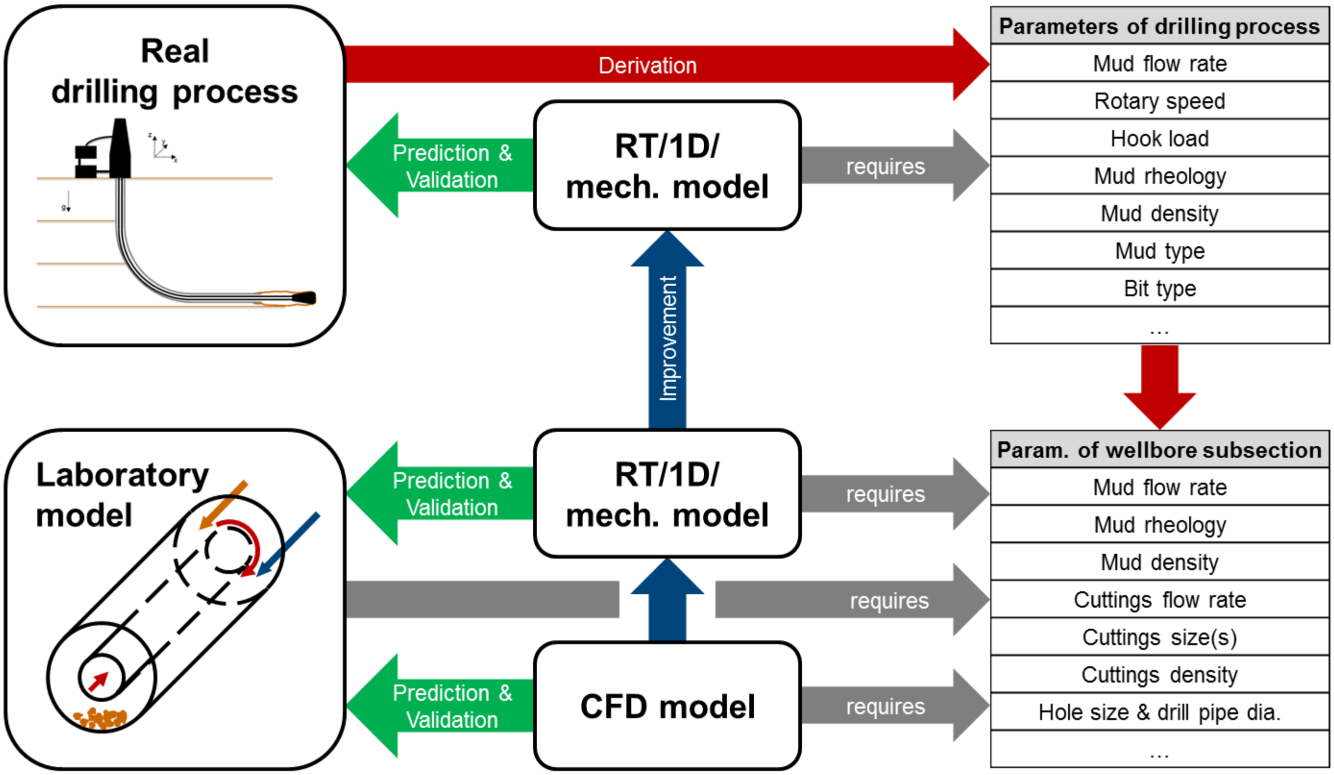

Figure 1 - Logical relationships of different type of research methods applied to cuttings transport modeling.

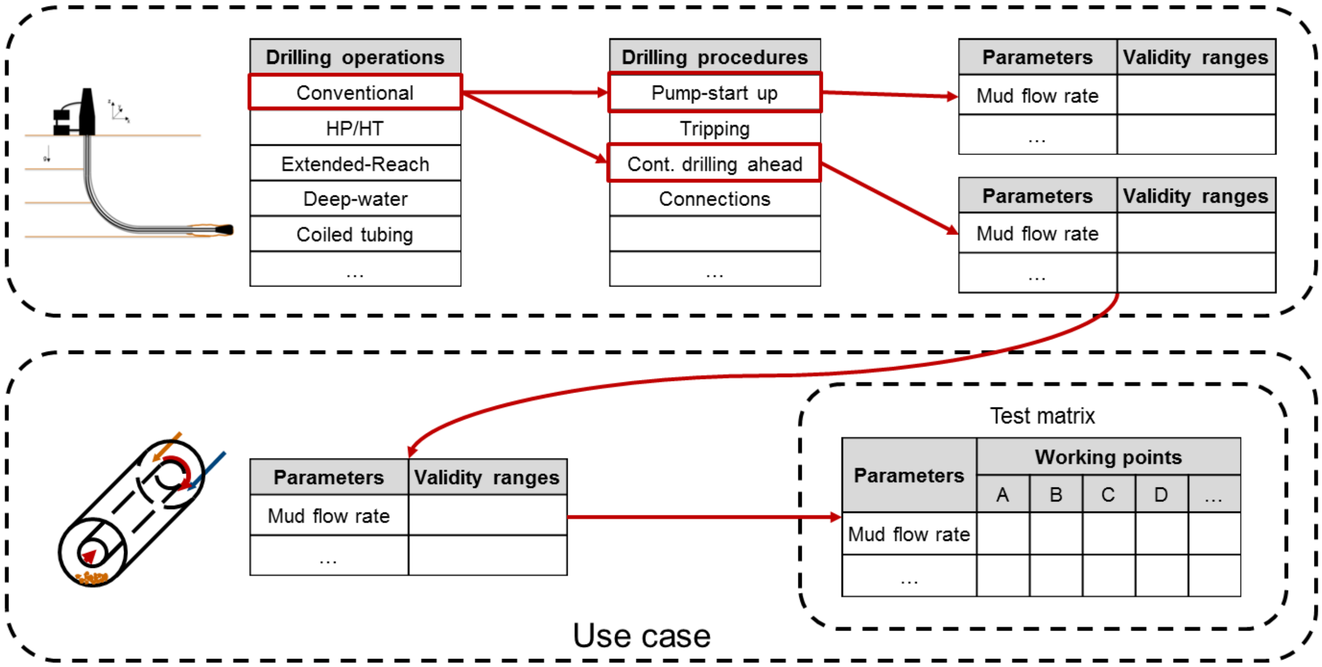

Figure 2 – Conceptual overview of derivation of parameter sets for cuttings transport problems.

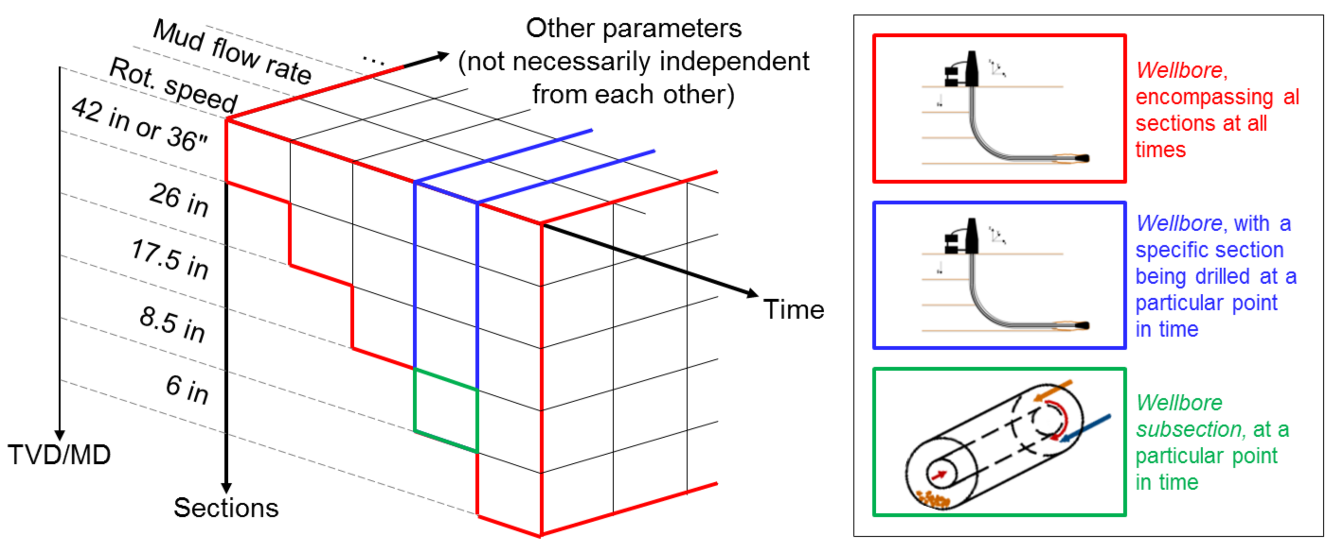

Figure 3 - Generic parameter space for cuttings transport problems.

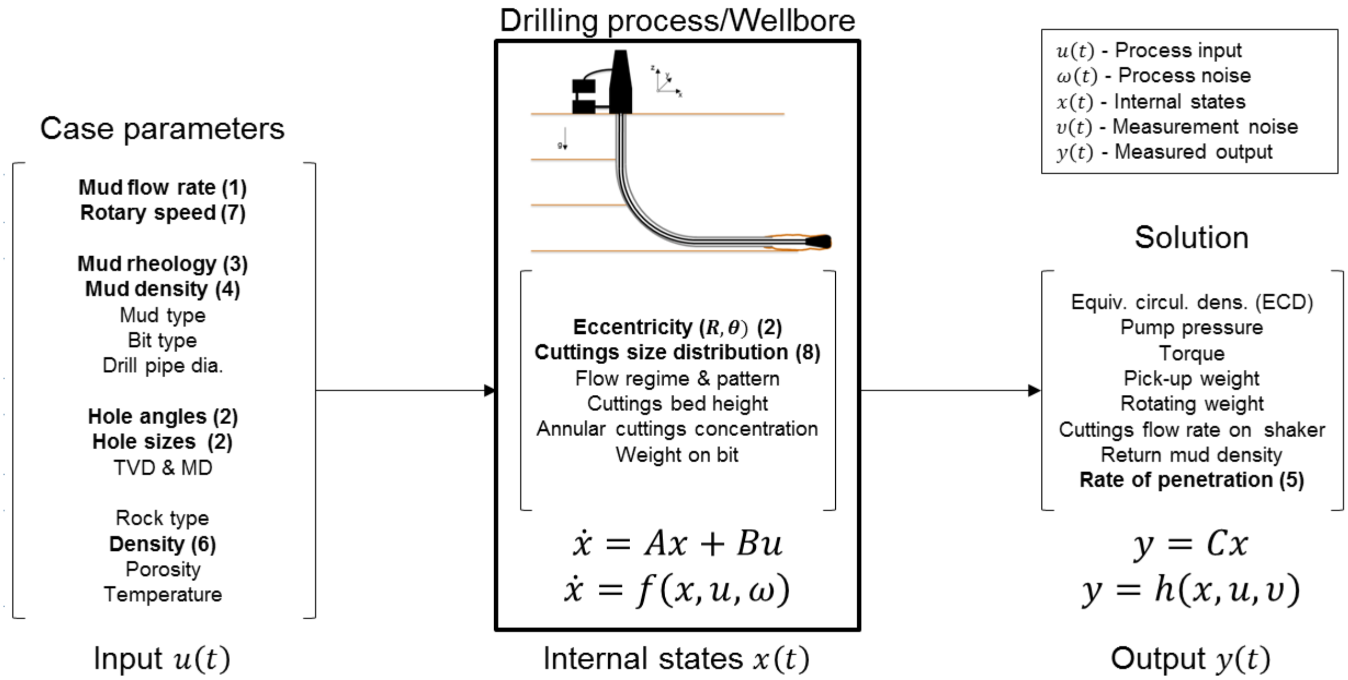

Figure 4 - Elaborated process view of (Nazari et al., 2010) for the drilling process.

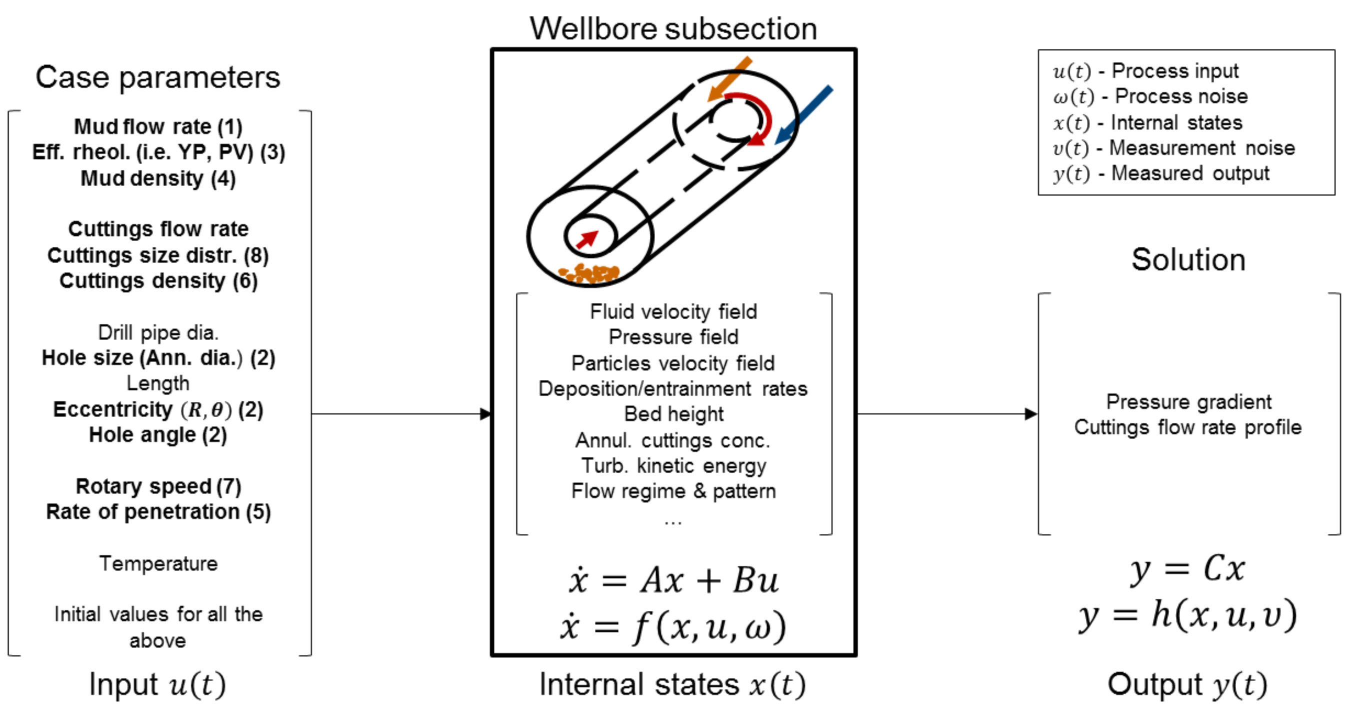

Figure 5 - Elaborated process view of (Nazari et al., 2010) for a wellbore increment downhole.

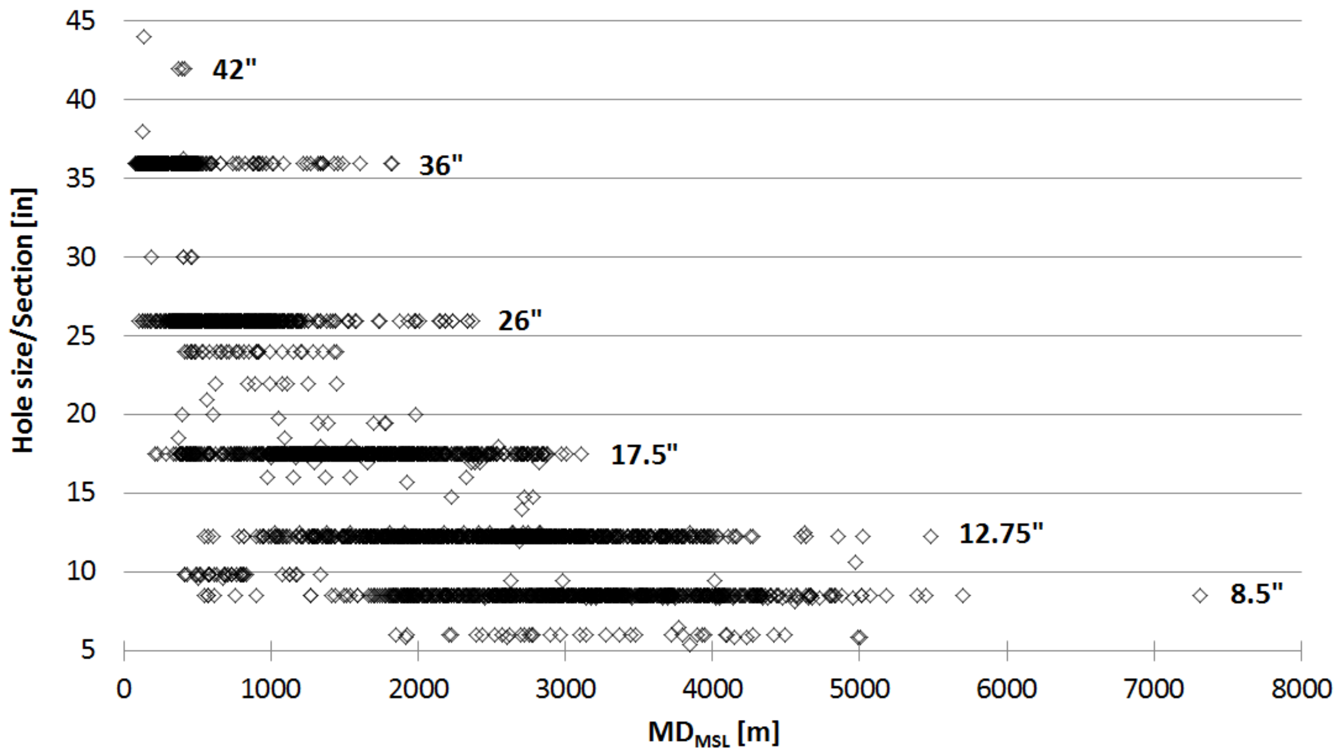

Figure 6 - Wellbore sections vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

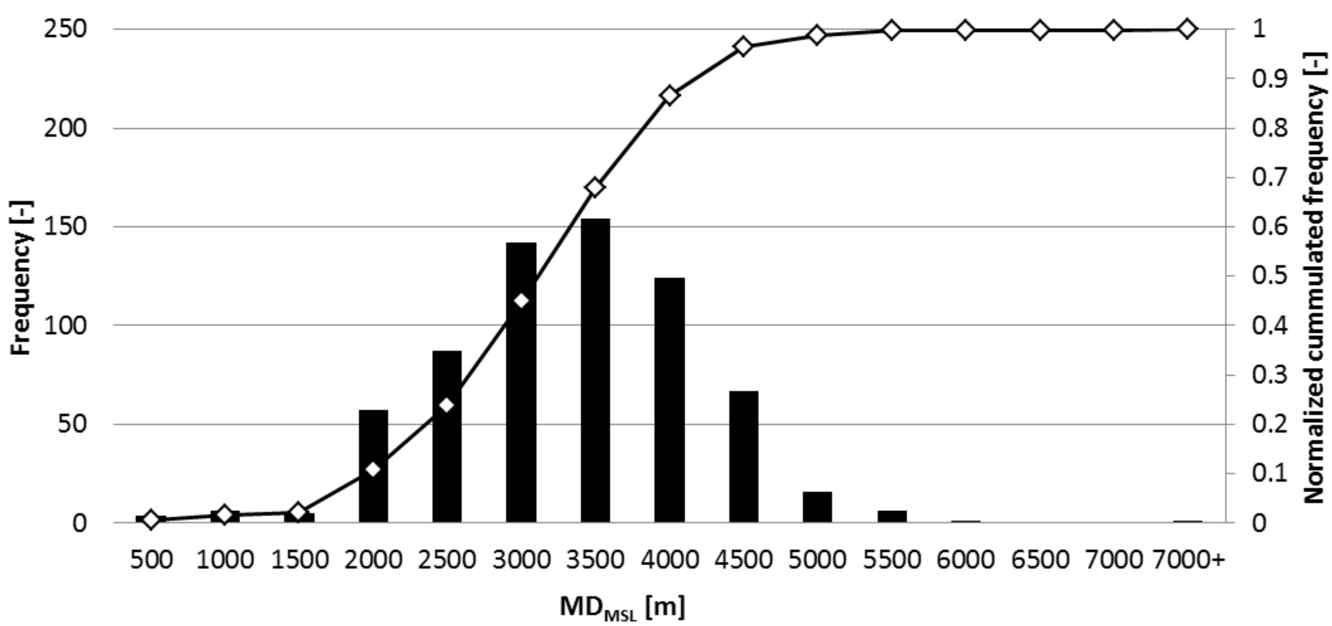

Figure 7 - MD_{MSL} distribution of 8.5" section of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

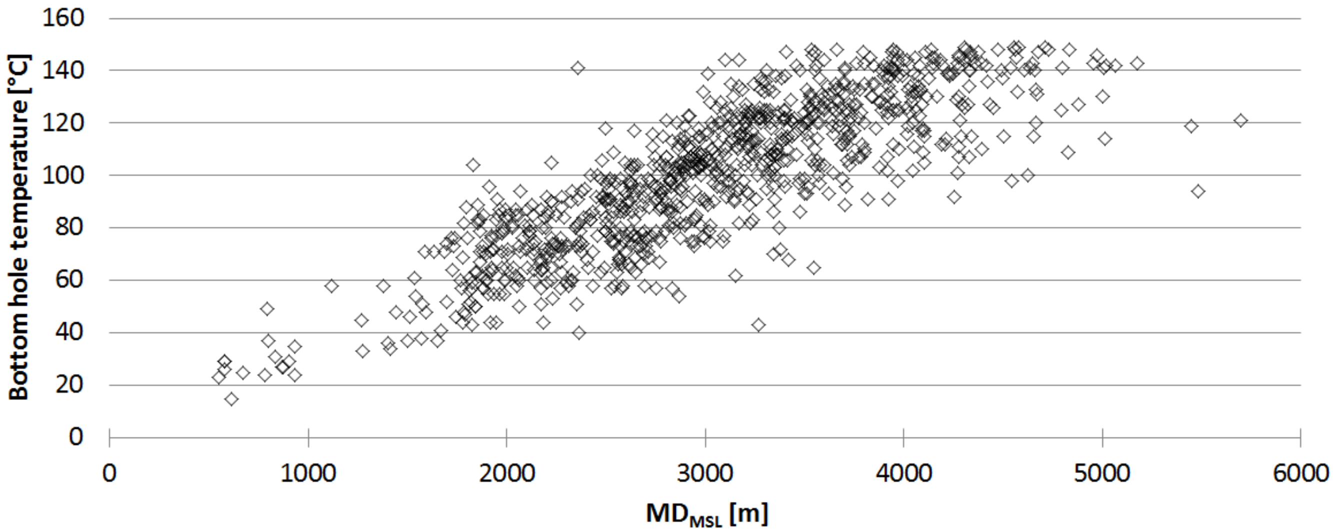

Figure 8 - Bottom hole temperature vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

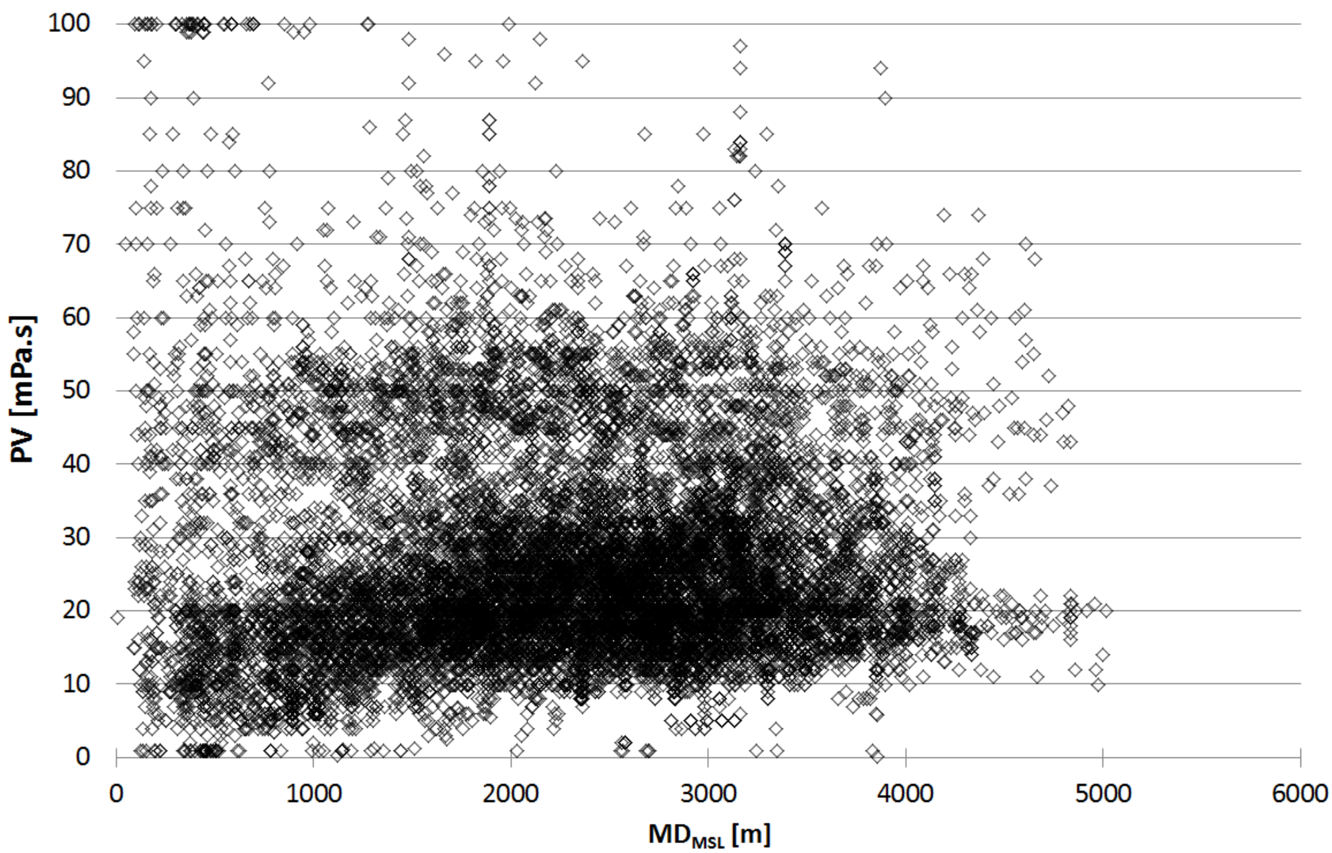

Figure 9 - PV vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

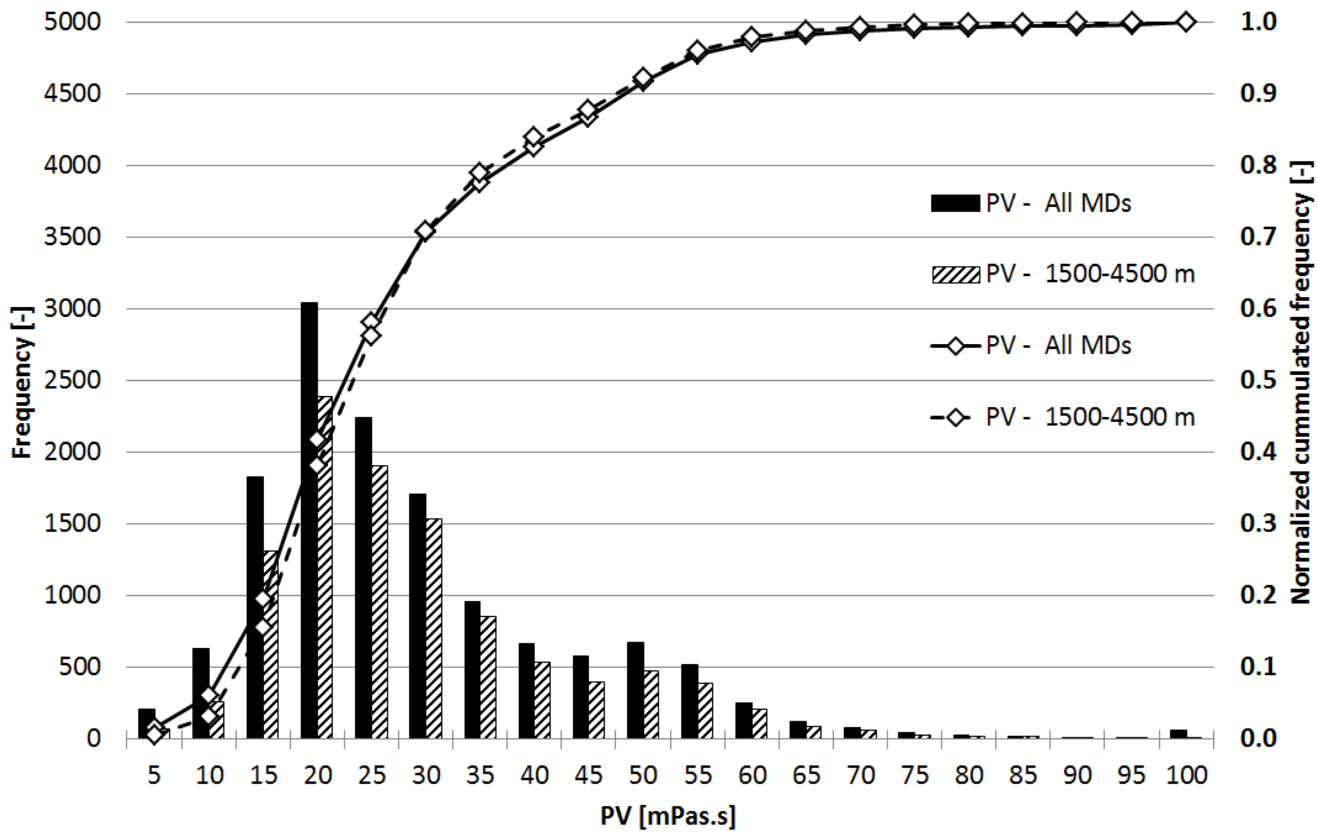

Figure 10 - PV distribution of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM, PV = 0 discarded ("FactPages of NPD," 2015).

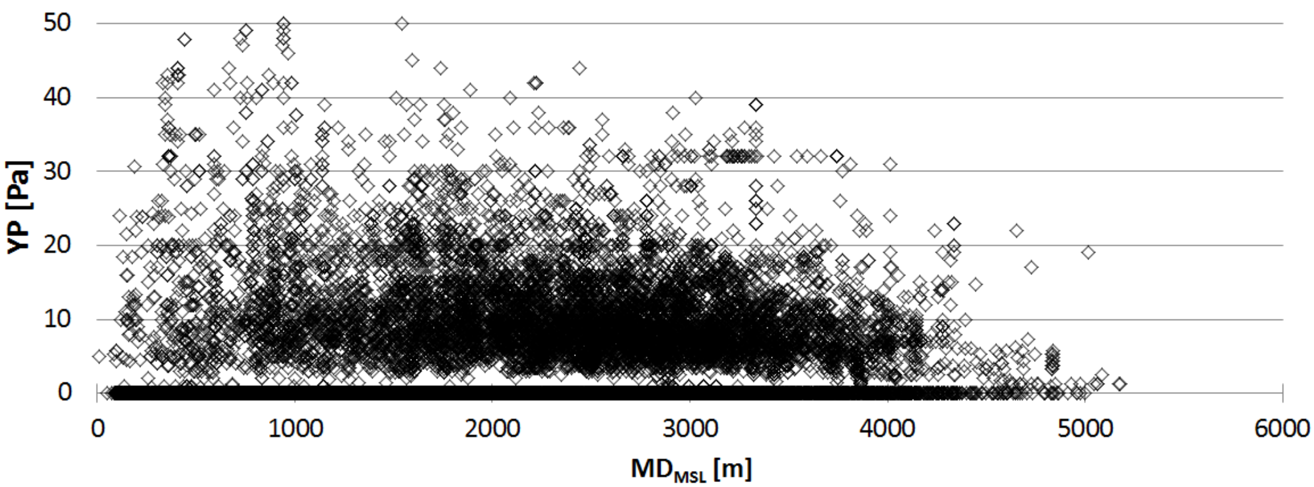

Figure 11 - YP vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

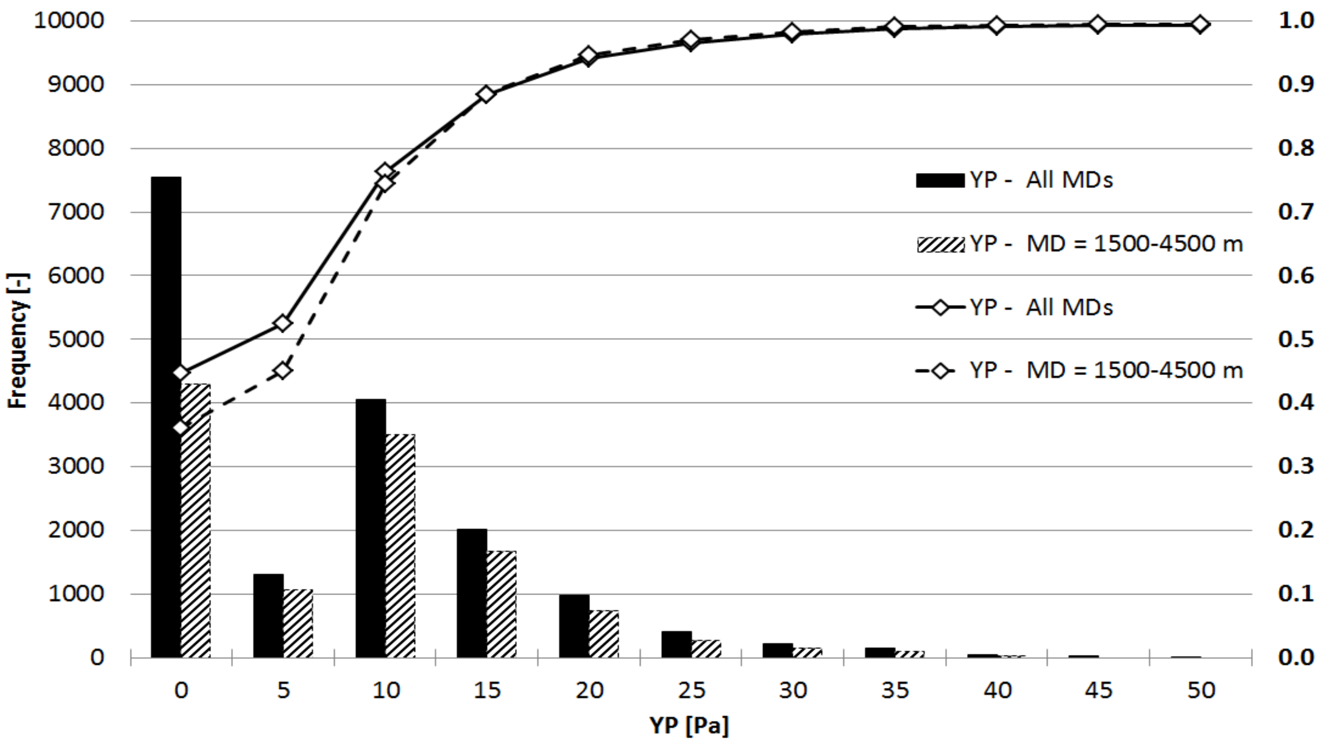

Figure 12 - YP distribution of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

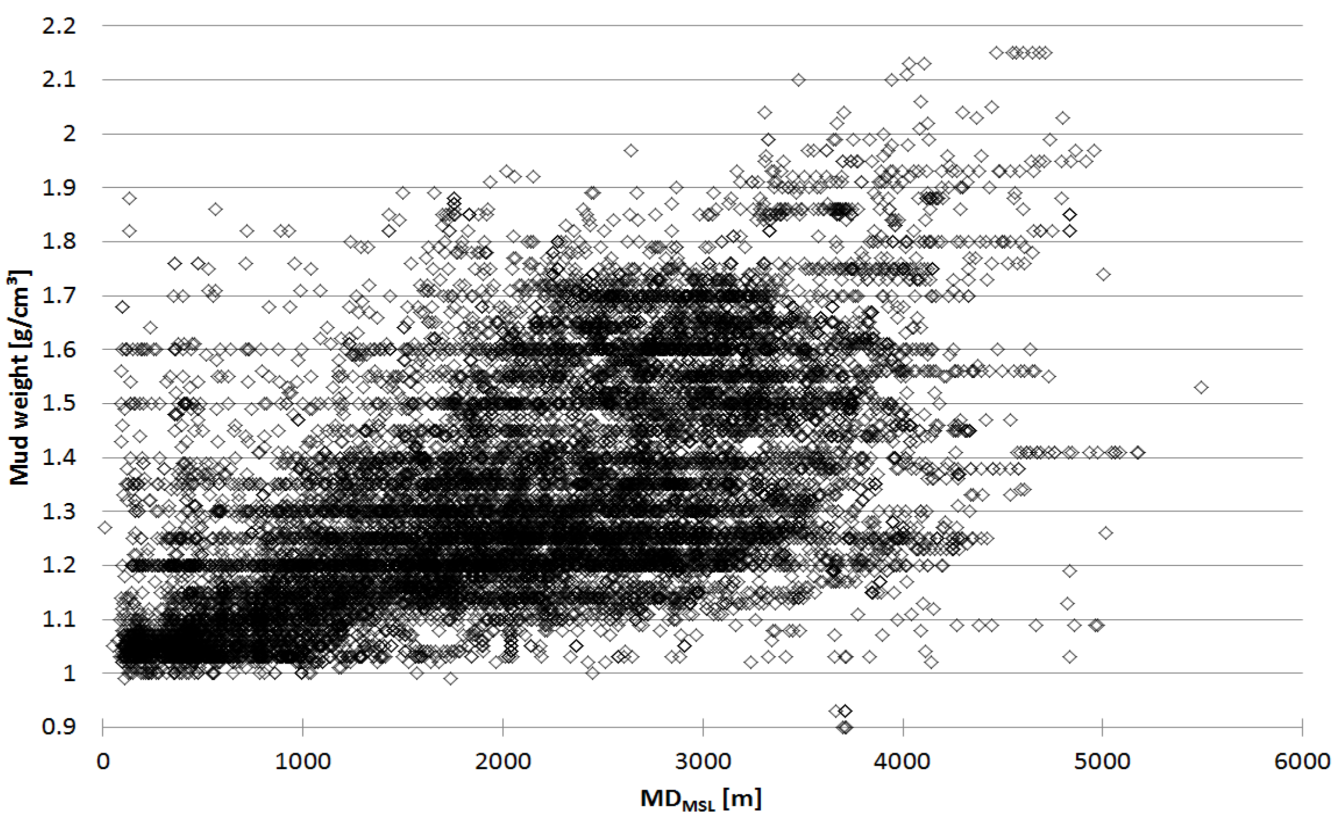

Figure 13 - Mud weight vs. MD_{MSL} of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

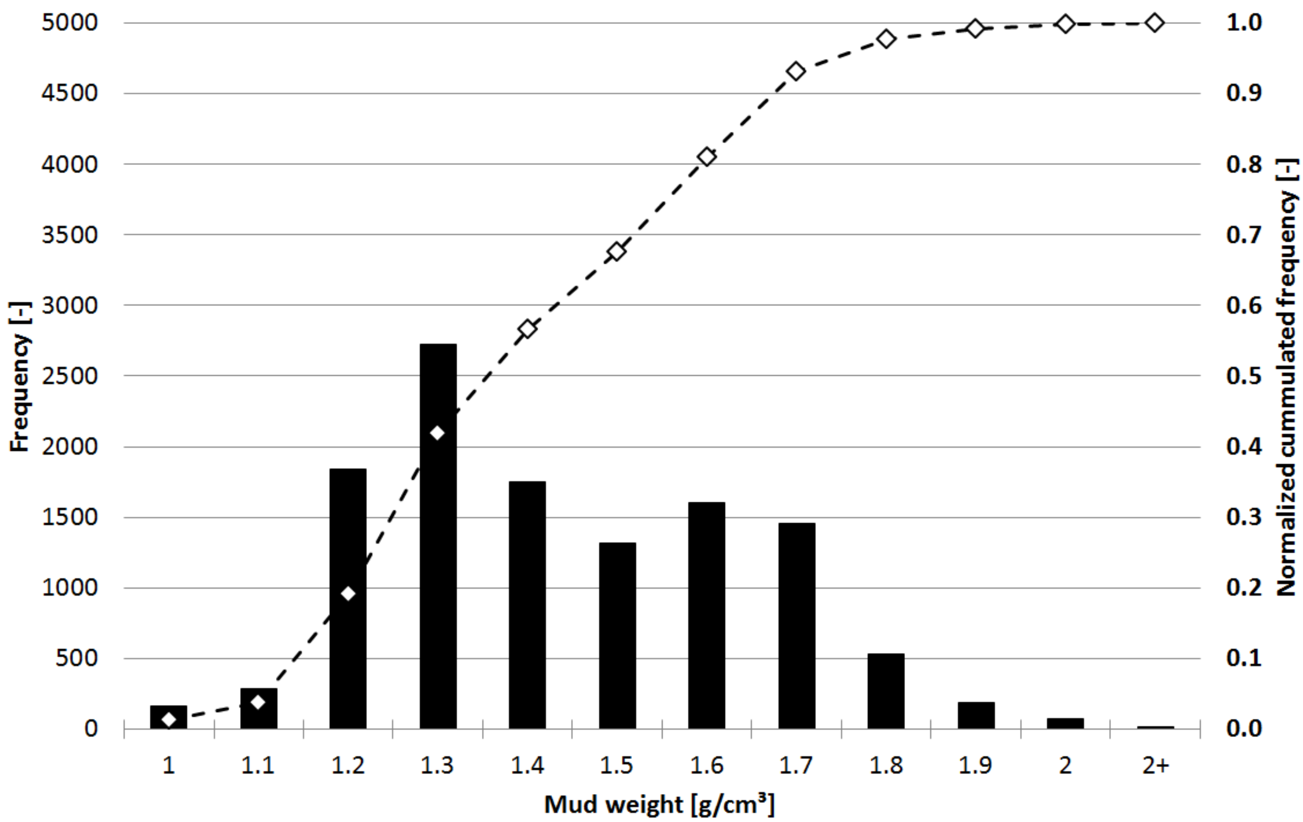

Figure 14 - Mud weight distribution of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM, MD_{MSL} = 1500-4500 m ("FactPages of NPD," 2015).

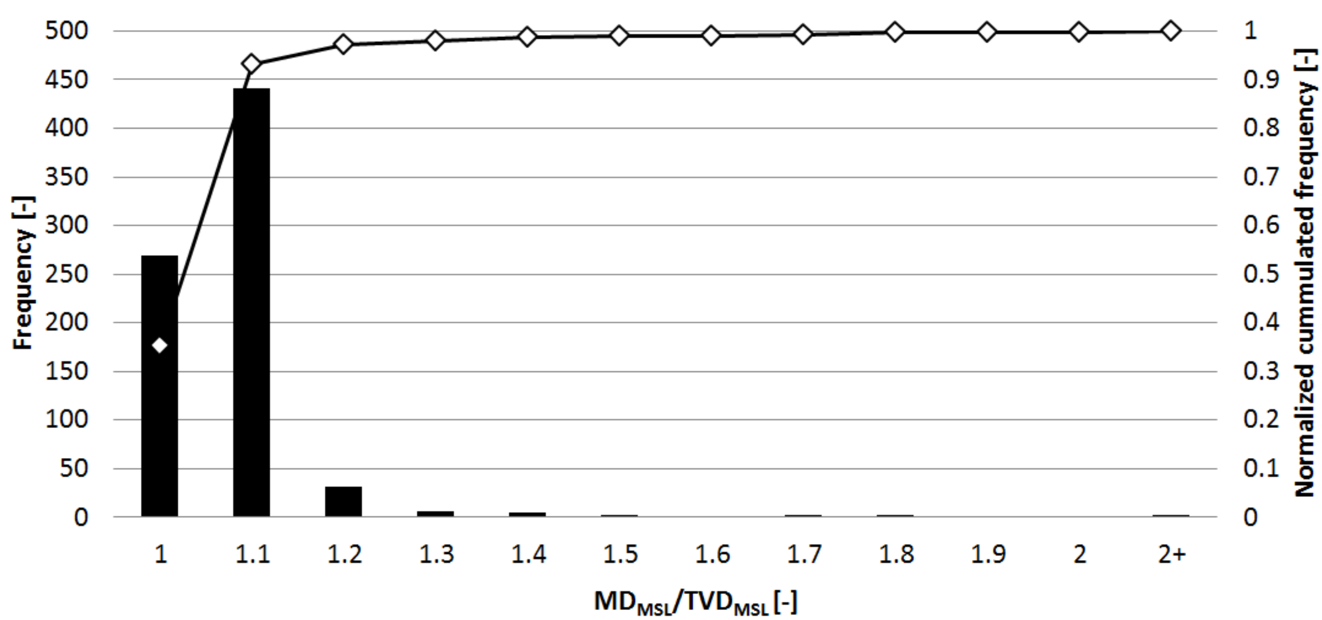

Figure 15 - MD/TVD ratio distribution of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

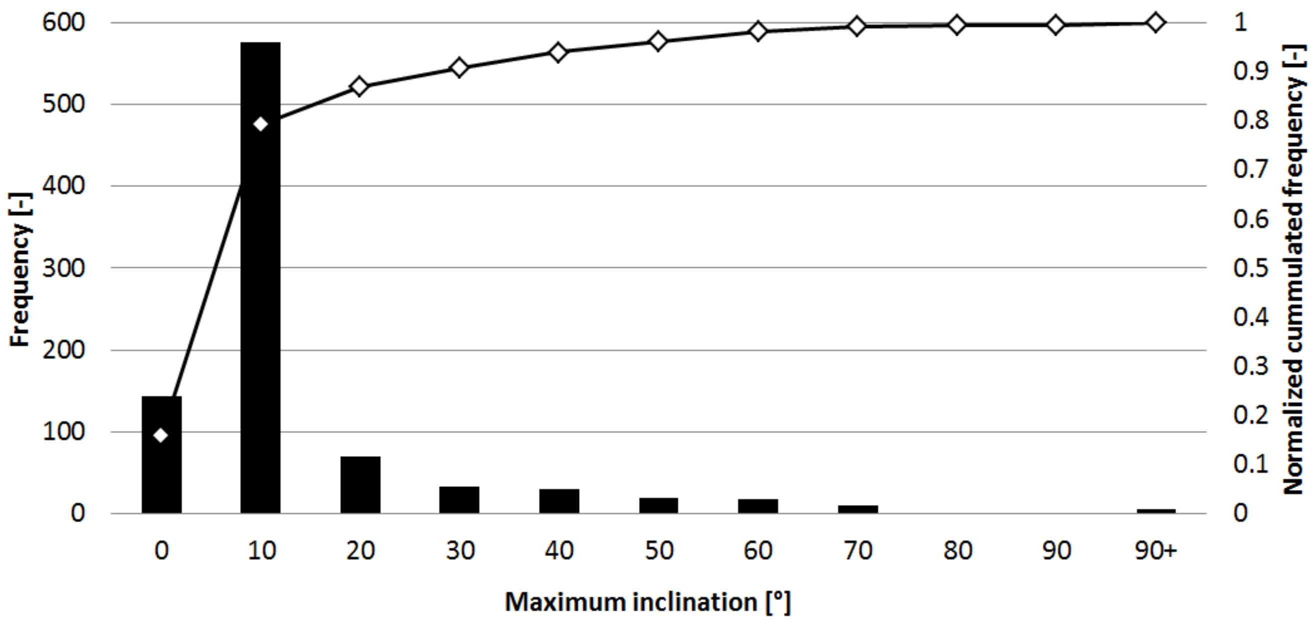

Figure 16 - Inclination distribution of NCS exploration/appraisal wells drilled between 1967 to 2015, bottomhole temperature < 150°C, mud type = WBM ("FactPages of NPD," 2015).

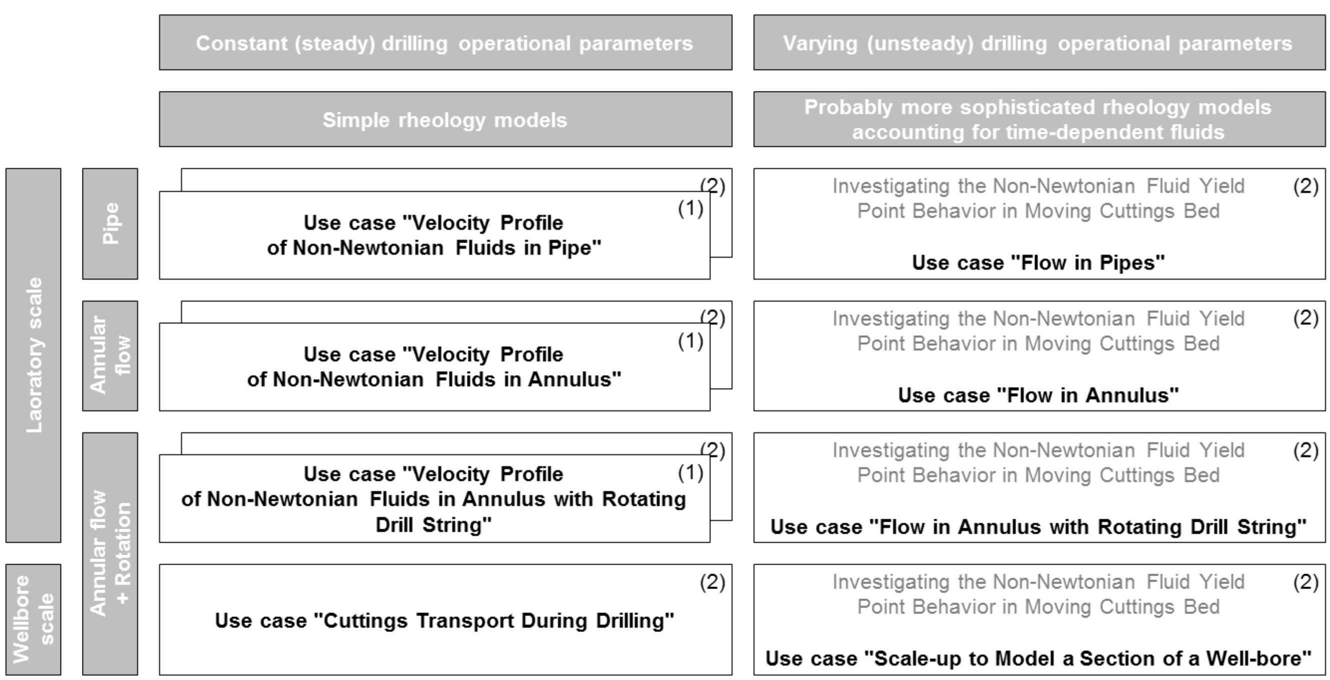

Figure 17 - Use cased defined for cuttings transport modeling based on (Meese, 2015), (1) Plain mud (Single phase flow), (2) Mud & cuttings (Multiphase flow).

Tables

Studies		**References**
Experimental/ laboratory		(Ahmed and Miska, 2008; Bizanti and Blick, 1983; Capo et al., 2004; Chen et al., 2007; Doron and Barnea, 1996, 1996; Duan, 2006; Duan et al., 2008; Garcia-Hernandez et al., 2007; Hosokawa and Tomiyama, 2004; Li and Walker, 2001; Miska et al., 2004, 2004; Nguyen et al., 2010; Ozbayoglu et al., 2007; Piroozian et al., 2012; Rabenjafimanantsoa, 2007; Ramadan, 2001, 2001; Sanchez et al., 1999; Sifferman et al., 1974; Taghipour, 2014)
Analytical/ numerical RT/mechanistic/1D	Conventional	(Campos et al., 1994; Cho, 2001; Clark and Bickham, 1994; Costa et al., 2008; Duan et al., 2009; Espinosa-Paredes et al., 2007; Ford et al., 1996; Garcia-Hernandez et al., 2007; Gavignet and Sobey, 1989; Guo et al., 2010; Hemphill, 1997; Hemphill and Ravi, 2010; Iyoho and Takahashi, 1993; Kamp and Rivero, 1999; Kenny et al., 1996; Larsen et al., 1997; Li et al., 2013; Martins and Santana, 1992; Masuda et al., 2000; Naganawa and Nomura, 2006; Nguyen and Rahman, 1998; Olasunkanmi, 2011; Petersen et al., 2008; Ramadan et al., 2005, 2003, 2001; Rasi, 1994; Salazar-Mendoza and Espinosa-Paredes, 2009; Santana et al., 1998; Sorgun, 2013; Wang et al., 2010; Xie et al., 2015)
	CT	(Cho et al., 2013, 2002, 2000; Kelessidis et al., 2002; Leising et al., 2002, 1998; Li and Aitken, 2013; Takahashi, 2003; Walker and Li, 2000)
	Foam	(Cheng and Wang, 2008; Duan et al., 2010; Osunde et al., 2006; Ozbayoglu et al., 2000; Rooki et al., 2014)
	Aerated	Naganawa, et al. (2002); Saasen (2004); Y. B. Adeboye and A. M. Akinribide (2013)
Computational Fluid Dynamics (CFD)		(Akhshik et al., 2015; Dykes, 2014; Xiaofeng et al., 2013b; Yilmaz, 2012; Hamne, 2014; Sun et al., 2014; Ofei et al., 2014; Ofei and Pao, 2014; Hajidavalloo et al., 2013; Reza Rooki et al., 2013; R Rooki et al., 2013; Mme and Skalle, 2012; Han et al., 2010; Al-Kayiem et al., 2010; Sorgun, 2010; Pereira et al., 2010; Wang et al., 2009)
Reviews		(Kamyab et al., 2012; Kelessidis et al., 2002; Kelin et al., 2013; Jeff Li and Luft, 2014; J. Li and Luft, 2014; Nazari et al., 2010; Pilehvari et al., 1999; Shah et al., 2014; Xiaofeng et al., 2013a)

Table 1 - Types of research methods with respective references.

Parameter	Characteristic range	Rationale
Mud flow rate	0…1325-1515…1700-2300 lpm	(Mims and Krepp, 2007)
Rotational speed	0…60…70-100 rpm	(Mims and Krepp, 2007)
Mud rheology: YP	0-20 Pa	Data analysis of (“FactPages of NPD,” 2015)
Mud rheology: PV	10-60 mPas	Data analysis of (“FactPages of NPD,” 2015)
Mud density	1000-1800 kg/m³	Data analysis of (“FactPages of NPD,” 2015)
Mud type	WBM	Project scope
Bit type	PDC	Typically used on the NCS
Drill pipe dia.	4-5.5"	Typically used on the NCS
Hole angles	0-90°	Including appraisal wells
Hole sizes	36-6"	(“FactPages of NPD,” 2015)
MD_{MSL}	1500-4500 m	Data analysis of (“FactPages of NPD,” 2015)
Rock type	Sandstone, Limestone, Clay	Typical formations on the NCS
Density	L: 1400-2900 kg/m³ S: 2000-2800 kg/m³ C: 1800-2300 kg/m³	(Fjaer, 2008; Schön, 1996) for rock types above
Porosity	S: 0.04-0.30 L: 0.04-0.30 C: 0.25-0.40	(Fjaer, 2008; Schön, 1996) for rock types above
Bottomhole temp.	50-150°C	Data analysis of (“FactPages of NPD,” 2015)

Table 2 - Wellbore characteristic parameter ranges for *drilling ahead* procedure in a *conventional* drilling operation with focus on the NCS and the 8.5" section being the section currently drilled in.

Parameter	Characteristic range	Rationale
Mud type	WBM	Project scope
Mud flow rate	0…1325-1515…1700-2300 lpm	(Mims and Krepp, 2007)
Mud rheology: YP	0-20 Pa	Data analysis of (“FactPages of NPD,” 2015)
Mud rheology: PV	10-60 mPas	Data analysis of (“FactPages of NPD,” 2015)
Mud density	1000-1800 kg/m³	Data analysis of (“FactPages of NPD,” 2015)
Cuttings flow rate	5-18 lpm	Based on (Bourgoyne Jr et al., 1986, p. 57)
Cuttings size	0.007-40 mm	(Aquateam et al., 2014; Rye, 2005; Saasen et al., 2013)
Cuttings density	2000…2800 kg/m³	(Fjaer, 2008; Schön, 1996) for sandstone
Porosity	0.04-0.30	(Fjaer, 2008; Schön, 1996) for sandstone
Drill pipe dia.	5.5-4.5"	Typical values on the NCS
Hole size	8.5"	Covers 0…90° hole angles, turbulence
Length of element	Open parameter	= f(Phenomena, comp. power, lab. space.,…)
Hole angles	0-90°	Exploration and appraisal wells
Eccentricity (e, θ)	0-1, 0-360°	Buckling of pipein all spatial directions.
Rotational speed	0…60…70-100 rpm	(Mims and Krepp, 2007), normal rot. BHA
ROP	0…5-30 m/hr	Typical values on the NCS
MD_{MSL}	1500-4500 m	Data analysis of (“FactPages of NPD,” 2015)
Bottomhole temp.	50-150°C	Data analysis of (“FactPages of NPD,” 2015)

Table 3 - Wellbore subsection characteristic parameter ranges for *drilling ahead* procedure in a *conventional* drilling operation with focus on the NCS and the 8.5" section being the section of interest.

State	Steady			Unsteady		
Phases	Mud + cuttings			Mud + cuttings		
Scale	Laboratory	Laboratory	Well	Laboratory	Laboratory	Well
Use case	**Velocity Profile of Non-Newtonian Fluids in Annulus**	**Velocity Profile of Non-Newtonian Fluids in Annulus w/ rot. Drillstring**	**Cuttings Transport During Drilling**	**Velocity Profile of Non-Newtonian Fluids in Annulus**	**Velocity Profile of Non-Newtonian Fluids in Annulus w/ rot. Drillstring**	**Cuttings Transport During Drilling**
Mud type	WBM	WBM	WBM	WBM	WBM	WBM
Mud flow rate	1500 lpm	1500 lpm	1500 lpm	= 100 lpm/s · t	= 100 lpm/s · t	= 100 lpm/s · t
Mud rheol.: YP	10	10	10	10	10	10
Mud rheol.: PV	21.3	21.3	21.3	21.3	21.3	21.3
Mud density	1000 kg/m³	1000 kg/m³	1000 kg/m³	1000 kg/m³	1000 kg/m³	1000 kg/m³
Cuttings flow rate	9.8 lpm	9.8 lpm	9.8 lpm	n/a	Initial cuttings bed	Initial cuttings bed
Cuttings size	0.25 mm	0.25 mm	0.25 mm	0.25 mm	0.25 mm	0.25 mm
Cuttings density	2560 kg/m³	2560 kg/m³	2560 kg/m³	2560 kg/m³	2560 kg/m³	2560 kg/m³
Drill pipe dia.	5.00"	5.0"	5.0"	5.0"	5.0"	5.0"
Hole size	8.50"	8.5"	8.5"	8.5"	8.5"	8.5"
Length of increment	10 m	10 m	10 m	10 m	10 m	10 m
Hole angles	40°	40°	40°	40°	40°	40°
Eccentricity (e, θ)	0, 0°	0, 0°	0, 0°	0, 0°	0, 0°	0, 0°
Rotational speed	0.0 rpm	50 rpm	50 rpm	0.0 rpm	50.0 rpm	50.0 rpm
ROP	20.0 m/hr	20.0 m/hr	20.0 m/hr	n/a	n/a	n/a
MD_{MSL}	4000 m	4000 m	4000 m	4000 m	4000 m	4000 m
Bottomhole temperature	135 °C	135 °C	135 °C	135 °C	135 °C	135 °C
Porosity	0.2	0.2	0.2	0.2	0.2	0.2

Table 4 – Case parameter sets (configuration data) of selected use cases.

Virtual modeling	This paper	Dykes (2014)	Dykes (2014)	Al-Kayiem, et al. (2010)	n/a	Akhshik, et al. (2015)	Akhshik, et al. (2015)
Experimental modeling		**Tomren (1986)**	**Sanchez (1999)**	**None**	**Taghipour (2013)**	**Tomren (1986)**	**Osgouei (2010)**
Mud type	WBM	Fresh water with no additives	Bentonite or polymer solution	Bentonite + Xanthan gum	WBM w/ Xanthan Gum & Laponite	Carbopol/High-viscosity bentonite	Water
Mud flow rate	0…1325-1515 …1700-2300 lpm	473-852 lpm	757-1892 lpm	2271-3407 lpm	193-492 lpm	377 lpm-757 lpm	94-234 lpm
Mud rheology: YP	0-20 Pa	n/a	7 Pa	42-55 Pa	3 Pa	7 Pa	n/a
Mud rheology: PV	10-60 mPas	1 mPa·s	7 mPa·s	9.5-15.7 mPa·s	4 mPa·s	18 mPa·s	1 mPa·s
Mud density	1000-1800 kg/m³	998 kg/m³	?	1013-1043 kg/m³	998 kg/m³	1013, 1018 kg/m³	998.00
Cuttings flow rate	5-18 lpm	3.4 lpm	5.8 lpm	2.6 lpm	1.0 lpm	3.5 lpm	1.3…2.6 lpm
Cuttings size	0.007-40 mm	6.350 mm	2.54, 6.350 mm	2.54, 4.45, 7 mm	0.9-1.6 mm	6.350 mm	2.000 mm
Cuttings density	2000-2800 kg/m³	2651 kg/m³	2640 kg/m³	2570 kg/m³	2700 kg/m³	2619 kg/m³	2300 kg/m³
Porosity	?	?	?	?	?	?	?
Drill pipe dia.	5.0"	1.90"	4.50"	5.0"	1.97"	1.90"	1.85"
Hole size	8.5"	5.0"	8.00"	9.88"	3.93"	5.0"	2.91"
Length of increment	Open parameter	12.192 m	7.620 m	0.910 m	12.000 m	12.000 m	7.000 m
Hole angles	0-90°	0,10,20 … 90	40°, 65°, 80°, 90°	15, 20, 25, 30°	0…30°	0, 20, 40, 60, 80°	90°
Eccentricity (e, θ)	0-1, 0-360°	-0.5, 0, 0.5	0-1 (Orbital motion)	0.00	0…1	0.50	0.623
Rotational speed	0…60…70-100 rpm	0, 50, 100 rpm	0, 25, …, 150, 175 rpm	0 rpm	0, 50, 150 rpm	50 rpm	0, 80, 100, 120 rpm
ROP	0…5-30 m/hr	15.2 m/hr	10.7 m/hr	?	8.0 m/hr	0.0 m/hr	18, 24, 30, 37 m/hr
MD_{MSL}	1500-4500 m	?	?	1710 m ("total depth of the well")	?	?	?
Bottomhole temperature	50-150°C	?	?	?	28 °C	?	?

Table 5 - *Wellbore subsection* parameter set developed in this study compared with parameter sets of recent cuttings transport studies.