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INVESTIGATION OF STATIONARY CUTTINGS BED HEIGHT IN WASHOUT

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Investigation of Stationary Cuttings Bed Height in Washouts

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Abstract

Knowledge of the amount of cuttings that have accumulated in a drilled wellbore is part of the information necessary for the effective control of bottom-hole pressure, preventing stuck pipe and minimizing circulation time for cleaning the wellbore. Acquisition of this knowledge can be made difficult when washouts develop in the wellbore, thereby promoting uneven distribution of cuttings along different sections of the wellbore. The cuttings are essentially found to accumulate in the washouts causing the wells to be improperly cleaned and can also lead to stuck pipe scenarios and a host of other events causing Non Productive Time. This study was therefore conducted to investigate the stationary cuttings bed height in washouts and how long and wide the washouts need to be before any increase in height was expected. This was achieved by a theoretical and experimental approach. The theoretical approach involved a literature survey of issues relating to wellbore washouts such as its causes, basic indicators of its occurrence in a well, its effects on wellbore drilling and tripping processes as well as possible ways of minimizing these effects. In a bid to further unveil the concept of washouts in wellbores, a physical model was developed in the course of the work. Furthermore, a mathematical model useful for calculating the stationary cuttings bed heights in the washouts was also developed.

The experimental work presented a detailed review of cuttings height in expansions. In order to verify this, a wellbore annulus with washout in the middle was simulated using a 6 m long loop. Three washouts of 60 cm, 30 cm and 15 cm in diameter respectively were used. The annulus was kept horizontal throughout the test period. Fluid flow rates were set in the frequency range of 5 to 30 Hz (28.6 l/min to 51.6 l/min). Water and aqueous solutions of hydroxyl ethyl cellulose polymer (HEC) were used for cleaning the cutting beds. Actual drill cuttings of were used. The stable cuttings bed height after long circulation as well as the effects of relevant drilling parameters was measured. During these tests, it was observed that a high Reynolds number leading to turbulent flow with low viscosity fluid (water) enabled cuttings to be removed in the largest washout diameter of 60 cm. It was equally observed that though cuttings accumulated in the washouts, it took an interval of 78 seconds at high flow rates for cuttings height increase to be seen in the largest washout, approximately 47 seconds for the 30 cm washout and 26 seconds for the 15 cm washout. This shows that washouts with wide diameters take much time to be filled with cuttings than when the washouts are smaller in diameter. However, the important issue here is the height of these cuttings in the washout sections.

Experimental results were used together with a non-linear regression analysis program to establish a functional relationship among drilling fluid properties namely the fluid flow rate and the cuttings bed height. Finally, the results of non-linear regression analysis showed that the relationship between cuttings bed height and flow rate of mud in washouts could be described very well by a simple log-decay exponential expression: $Q = ae^{bH}$.

Table of Content

PAGE

7. DISCUSSION AND EVALUATION

List of Figures

List of Tables

1. Introduction

Drilling deep wellbores, especially with inclined trajectories, is becoming increasingly common in challenging environments such as centrally installed offshore platform in deepwater, tectonically active areas and subsalt regions. Exploiting these hard-to-reach resources is usually accompanied by tough challenges in maintaining borehole stability. According to recent estimates, about 40% of Non-Productive Time (NPT) is attributable to geopressure and geomechanical issues such as stuck pipe, lost circulation, kicks, shallow water flows, sloughing shale and wellbore instability (Azeemuddin and Ong, 2006). Operators worldwide lose billions of dollars every year to drilling problems caused by time-dependent wellbore instability in clay-rich shale formations. The term "instability" is used in the drilling industry to cover all problems associated with incompetent borehole walls, such as sloughing, hole enlargement, washouts and tight hole.

Wellbore washouts are one of the most challenging time dependent cases of wellbore instability. They may contribute to one or more of the following: hole cleaning difficulties, stuck pipe, bridges and fill up, increase in mud volume and treatment cost, increase in cement cost, poor cementation due to low displacement rate and/or channelling, difficulties in running logging tools and poor quality of critical formation evaluation data. Washout problems are closely connected with the "bulk properties" of the shale (strength, water content, clay content). The drilling-fluid bulk properties also are of importance. These variables are interconnected and influence the overall behaviour of shales during drilling.

Many operators and service providers treat shale-related wellbore instability, especially washouts, as largely unavoidable, grit their teeth, drill through the washout section quickly, and run extra casing. Not only is this approach more expensive, but also a smaller hole size in the pay zone can impact production rates for years to come. Often drillers switch from water-based to oil-based mud, assuming this will automatically remedy the situation. However, shale problems can still occur with oil-based mud, especially when the underlying mechanisms are poorly understood. Some operators may have a geomechanical service provider perform a study of the geomechanical wellbore instability component while another service provider designs the drilling fluid. Many drillers establish local “rules of thumb” by trial and error. Unfortunately, the “error” part of that equation may cost millions of dollars and create unnecessary delays.

One hypothesis in the present investigation is that the hydraulically controlled cuttings bed height in washouts is a function of the fluids Reynolds number. It is therefore imperative to find out how long and how large the washouts need to be before any increased bed height is to be expected. The hydraulic entrance effect of the washout will play an important role. The end product is of high interest for tripping operations. It is believed that the major cause of mechanical stuck pipe and pack offs is a result of the shovelling of cuttings when the BHA, passes by the washouts.

The long term goal of this project is to study the theoretical and experimental stable bed heights in wellbores after long term circulation with cuttings feeding. In order to reach this goal, we need to go stepwise ahead:

- Study of relevant published knowledge on cuttings bed height in washouts
- Physical and mathematical model of the problem
- Theoretical investigation of cuttings bed heights in expansions as a function of drilling parameters.
- Experimental investigation of the cuttings bed heights in smooth hole and expansions.

2. State of the Art on Washouts, Cutting Bed Height and Other Restrictions

Based on available published research work dealing with causes of washout and their potential consequences of tripping through them as well as through stationary cuttings bed height, a few papers focus on mud rheological properties as it affect tripping through washout sections and downhole restrictions causing lost circulation. A critical analysis of all research work regarding tripping, washout sections, and stationary cuttings bed and down hole restriction demonstrate that the common point between them is: the washout section of the hole leads to increase in hook load, overpull and the incidence of stuck pipe in wells.

For the purposes of this research work, a few available important contributions from various works on washout, their potential consequences of tripping through them and downhole restrictions like packoff causing lost circulation are reviewed below.

The following subheads are adopted in order to streamline this review:

- The physics involved in the evolution of washouts
- Cuttings accumulation in washouts
- Detection of downhole washouts through surface parameters during tripping operations.

2.1 The Physics Involved In the Evolution of Washouts

To understand the basic physics involved in the evolution of washouts, this section will review the definition of washouts from some authors, factors leading to washout development, key indicators of washout development in wellbores, effect of washout on wellbore cleaning, how to minimize washout development, and other washout issues such as prevention of washout.

2.1.1 Definition of Washout

Washouts have diverse definition depending on the authors, but one common denominator they have is that the hole or wellbore diameter enlarges than its original size.

Schlumberger (Slb 2012), define a washout as an enlarged region of a wellbore. They further added that it is an open hole section which is larger than the original hole size or size of the drill bit.

2.1.2 Why the Study of Washout Is Important

It is very important to know actual hole diameter and presence of washouts in order to calculate the exact volume of cement required to set casing in place. Caliper logs are run with wireline to determine the exact hole diameter with depth.

It is also necessary to know when washouts occur in a wellbore because these zones are good places where cuttings could accumulate and cause stuck pipes which lead to NPT. It is important here to note the formations that are prone to washing out. These include:

- Weak and soft formations: Hole erosion and washout occur across weak and soft formations as a result of using large flow rates resulting in excessive mud annular velocities.
- Washouts also occur across reactive shales which slough into the hole when contacting uninhibited water-basedmud.
- Washouts also occur in sands and sandstones.

2.1.3 Factors Leading To Washout Development

Schlumberger (Slb 2012) stated that washout can be explained basically by two mechanisms: borehole collapse of a portion of the wellbore due to insufficient mud weight and/or hole erosion due to improper mud chemistry design.

Skalle (2011) posted that washout can also be caused by:

- High WOB in laminated formations, (alternating hard stringers and soft layers)
- Hydraulic and mechanical erosion of the weakened formation, and
- Swelling of shale and clay as it contacts freshwater thus weakened the formation.

Similarly, Azar and Samuel (2007) pointed out that enlargement of borehole, commonly referred to as washout is caused by hydraulic erosion, mechanical abrasion due to the drill string, and inherent sloughing of shale formations.

In addition, in the webpage, www.scribd.com/doc/34410470/Shale-Problems (2013), states that washout occur mainly as a result of the dispersive nature of soft reactive shale, leading to hole enlargement, and that the effect is mainly associated with Water Based Muds and is rear in oil based muds. They paper in its conclusion states that washout can lead to problem of hole cleaning and difficulty in running into hole, plus poor cementing jobs, etc.

Chemerinski and Bills (1995) in their different opinion on the subject matter, claim that the causes of borehole washouts are numerous and that annular velocity is falsely blamed for the erosion. They added that in unconsolidated sands, decreasing the flow rate does not lead to a better gauge hole. Besides decreasing the flow rate decreases the annular velocity, but it also decreases the nozzle velocity, the hydraulic impact, and the hydraulic horsepower at the nozzles.

Nguyen (2012), pointed out that packoff can result either in an enlarged hole or an under-gauge hole. He added that the enlargement occurs when the drilling mud contains a water phase having salinity less than the saturation point. This causes the salt to dissolve in the water, washing out the hole. To keep this from happening, he suggested that operators can use non dissolving salt water or oil based muds.

Saleh and Mitchell (1989) from a wholistic point of view, states that borehole washout or hole enlargement as a result of hole instability (during the drilling operation) may be caused by one or more of the following:

1. State of the underground stresses
   - Tectonic stresses
   - Hoop stresses due to overburden load
   - Gravity force due to formation
2. Thermal stresses
3. Stresses induced by pressure gradient between formations pores pressure and wellbore pressure associated with the flow of formation fluid to the wellbore.
4. Chemical activities / reaction between well bore fluid and its filtrate with formation rock and its fluid content. As in alteration of rock strength and swelling of the rock with associated strain and swelling pressure
5. Mechanical drag on wellbore wall caused by drill string
6. Hydraulic drag caused by annular pressure losses, jet impact forces, surge pressure, etc.

Finally, Dittmer (1967) based on field experience in Arkoma Basin air/gas drilling operations found that:

1. Wellbore washout or hole enlargement in drilling occurs as a result of both erosion and sloughing.
2. Erosion is largely caused by the drillstring wearing away the rock.
3. Erosion caused by the drillstring is most severe in a dog-leg hole and to a lesser extent in an inclined hole.

2.1.4 Key Indicators Washout Development in Wellbores

Key indicators that would enable a driller to know that a washout has developed in a wellbore are here treated.

(Roughneck city 2012), the webpage presents several observations indicating that washout has developed in a well bore while drilling, such as:

- Excessive cuttings return at surface,
- Excessive hole fill after tripping,
- Mud volumes in excess of calculated amount,
- Oversize hole from LWD calipers, etc.

Similarly, the following are the symptoms of hole washout according to (Scribd 2012)

- Increase in cutting volumes
- Directional problems
- Bottom up time increases
- Difficulty running in hole due to ledges
- Packing off increase over pull and drag
- Poor hole cleaning leading to packing-off of the BHA

2.1.5 Effects of Washouts on Wellbore Drilling Operations

Wellbore washouts have numerous effects on wellbore drilling operation according to the submissions of the following authors:

Eck-Olsen (2010) revealed that washout have the following effects on wellbore drilling:

- Sand beds in horizontal sections → tripping problems
- Poor cementing → perforating, sand control, production and stimulation problems
- Hole enlargements → difficult tripping → side tracking or plugging (expensive)
- Hole enlargements → low flow velocity → bad hole cleaning
- Pieces of rock and sand are falling into well → stuck drill pipe
- Washout bridges → increase annular pressure → fracture and lost circulation

The document on webpage (Tamu 2012) took a critical look at the numerous effects of washout on well logging tools. These effects include: “The possibility of having a seriously degraded log data quality due to rapid changes in the diameter of a hole and in sections where the wellbore diameter is greatly increased or has been washout. The results of these effects is impaired logging by causing “bridging” or “tool sticking” and increase the volume of fluid between the formation and logging tool. Deep investigation devices, such as resistivity and velocity tools are least sensitive to borehole effect. Nuclear measurements (density, neutron, porosity, and both natural and induced spectral gamma-rays) are more sensitive due to their shallow depth of investigation and because of the effect of increase volume of drilling fluid on attenuation of neutrons and gamma rays. This effect is as shown in figure 2.1. Correction can be applied to the original data to reduce these effects. However, one cannot correct for very large washouts”

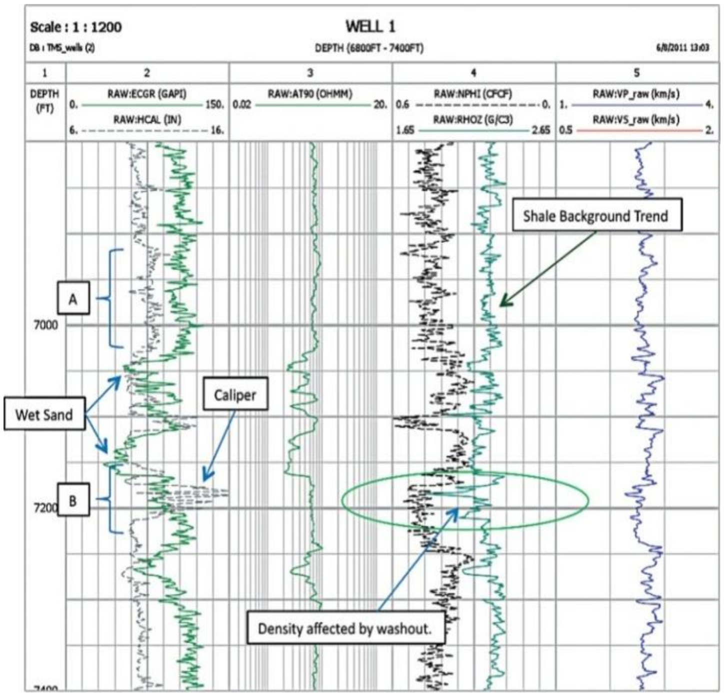

Figure 2.1: Effect of washout on well-logs (Geoscience world, 2008)

Azar and Samuel (2007) hold a similar view to Eck-Olsen (2010), when they submitted that the associated problems of wellbore washout include difficulty in cementing, potential hole deviation, an increase in hydraulic requirement for effective hole cleaning, and difficulty in some logging tool operations.

Chemerinski and Bill (1995) in another view in their paper titled: “Hydraulic wellbore erosion while drilling”, submitted that: Boreholes frequently “washout” or enlarge after drilling and when this happen a borehole enlarges, several detrimental effects are observed. Some of them are:

- Cementing problems are accentuated. Cement will frequently not fill large washout intervals that can cause leak behind casing.
- Logs are frequently difficult to interpret. Stand-off distances will have variable distances from the formation, creating interpretation problems.
- Cutting and drilling fluid disposal costs increase.

Steve et.al (1995) in his view on the effects of washout on BHA posited that salt is soluble and that under certain conditions, salt will dissolve and the result is borehole enlargement. This according to them will cause unpredictable directional tendencies, poor BHA performance stability issues. They further added that hole washout, caused by hydraulic erosion or dissolution of the salt, can also cause steerability problems for the directional tool. Hole washout causes further steerability problems with push-the-bit RSS.

Burke et.al (1995) in his shale chemistry perspective pointed out in a drilling scenario, that water reacts with the wellbore, expanding the hydrophilic clays and that sloughing of the clays into the hole increases the size of the annulus, causing hole washout. They added that in the Gulf of Mexico, 30% hole washout is common, and over 100% washout has occurred over short sections of a wellbore. They claim that the annulus increases and the annular velocities decrease, removal of cutting from the hole becomes increasingly difficult.

Other effects according them are hydration of hydrophilic clays which can lead to increased torque and drag on the drill string, bit balling (clogging of clays in the drill bit), and often a stock drill pipe. They submitted that when the drill pipe becomes stock, drilling activities are often shut down while a number of measures, including the addition of diesel pills or other spotting fluids, are excessively used in attempt to free the stock pipe. The highest direct cost of stock pipe is the loss in productivity and from a pollution standpoint, the volume of mud and cutting discharged will also increase if the hole needs to be drilled.

Saleh and Mitchell (1989) in his general point of view pointed out that borehole washout or hole enlargement may contribute to one or more of the following:

- Increased in cement cost
- Difficulties in running logging tools
- Poor cementation due to low displacement mud rate and/or channeling
- Hole cleaning difficulties
- Bridges and fill up
- Stuck pipe
- Increase in mud volume and treatment cost

Effect on lag time:
A washout creates a larger annular volume that requires more pump strokes to circulate from the hole. Therefore, if the actual lag time is greater than the calculated time, a washout exists.

2.1.6 How to Minimize the Effects of Washouts

The following are some of the various ways of bringing the effects of washout to a minimum.

A review of how to minimize the effects of washouts as compiled in a stuck pipe self (Roughneck city 2012) reveals that:

- Casing while drilling
- Use of appropriate mud types, mud additives and increased mud density can minimize washouts and

- Use of top drive to allow back reaming and circulation when pulling out of the hole considerably minimizes the effects washout have on wellbore cleaning operations.

In addition to the above, in the webpage, no.34410470, (2012), Suggest the following ways of minimizing hole washout

- Increasing mud inhibition (water based muds), by using appropriate salt/raising salt level and if available, by adding glycol (e.g. BP Chemicals DCP 208 or 101). Glycols harden soft shale's so reducing dispersion/erosion.
- Improving low shear rheology of mud (higher YP and higher gels) to ensure good hole cleaning, this will help to clean washout sections and prevent cutting slip. Alternative regime is to use turbulent flow conditions (low viscosity mud).
- Maintaining mud circulation to prevent cutting slip.
- When making trips, POOH slowly to minimize swab/surge pressures.

Fleming (1986) in his experimental work, compared two wells as to washout, mud cost drill, hours spent drilling, hours spent washing and reaming, and total circulating time (excluding drilling). The section of the wells he used for the comparisons were 8½ inches hole appropriately 1100 feet in length. The sections were correlated using the D-5 and D-10 sands and divided into fourteen intervals. In the end, he submitted that: the use of potassium hydroxide (KOH) in a mud system lightly treated with polymers helps to provide shale stability by reducing water absorption rate at the borehole drilling fluid interface. The unique action of potassium in these system according to him is partially responsible for its ability to control wellbore stability caused by shale hydration and that elimination of strong dispersants also has aided in combating the hole erosion. The mud reduced hole enlargement, cuttings dispersion and mud costs in comparison to the lignosulfonate mud used in another well. He recommended that the use of lignosulfonate dispersants be reduced or if possible, eliminated.

Finally, Bennion (1999) said that certain formation components (halite, various shale, anhydrite, etc) may have limited to high solubility in water based fluids. This to him can result in poor gauge hole formation washouts or collapse in certain conditions. He concluded that oil based fluids, inhibited fluids or saturated ionic systems are often used to combat these issues.

2.1.7 Reported Cases Where Wellbore Washouts Have Occurred

(a) Gulf of Mexico: Burke et.al. (1995) pointed out that in a drilling scenario, water reacts with the wellbore, expanding the hydrophilic clays and that sloughing of the clays into the hole increases the size of the annulus, causing hole washout. They added that in the Gulf of Mexico, 30% hole washout is common, and over 100% washout has occurred over short sections of a wellbore. They claim that as the annulus increases and annular velocities decrease, removal of cuttings from the hole becomes increasingly difficult**.**

(b) Niger Delta Area, Nigeria: According to Omuvwie et.al. (2009), significant borehole washout is often seen in shale sections in many of the older wells drilled in the Niger delta area of Nigeria. This is due partly to the use of water-based mud, in compliance with government regulation, and long open hole exposure time, among other causes, (Avu et al, 2004). The degree of washout is indicated by callipers readings. It is understood that the density tool being a padded and shallow investigation tool, tends to read mud density where there is hole caving. On the other hand, the sonic tool is thought to do better where washout is moderate, hence the practice of reconstructing density from sonic in bad hole sections. However, synthetic seismograms created from such logs often show a hard kick at the shale-sand interface, indicating that the sands are acoustically harder than the shale, contrary to the predominant trend in the Niger delta. Furthermore, such synthetics are often of reverse polarity to the measured seismic, hence acceptable well-to-seismic ties are only achieved by stretching/squeezing and applying time shifts and/or phase rotation of the wavelets. Such ties are far from accurate and could lead to interpreters picking the wrong loops.

2.1.8 Preventing Hole Washout

Prevention of hole washout will eliminate loss of rig time and cost of drilling. In order to prevent a hole from being washout, there are certain actions that should be taken. A few of these actions are highlighted in this section.

Scribd (2012) highlights a few of these actions namely:

- Establish shale reactive prior to drilling (e.g. by reviewing offset data, and/or running laboratory test).
- Select appropriate level of mud inhibition. Use glycol mud in soft reactive shale if water based mud is to be used.
- Use mud with good hole cleaning properties.

Other ways of preventing hole washouts as shown by other authors include:

(a) Use of Mixed Metal Hydroxide: The mixed-metal hydroxide (MMH) water-based system is formulated by developing a strong complex between the MMH viscosifier and bentonite. This complex forms when the MMH, with an electron-deficient lattice, is added to water and bonds to the cation exchange sites on bentonite." The result provides a highly shear-thinning fluid, exhibiting a high yield point, low plastic viscosity, and high, flat gel strengths. Those properties can be retained under elevated temperature and pressure conditions.

These unique rheological properties give excellent solids suspension and hole cleaning capabilities, yet the fluid screens easily, even at" high flow rates. Highly shear-thinning fluids allow low pump pressure, which often results in elevated penetration rates with good bit hydraulics. This may provide one solution to some shale instability problems, since increased penetration rates achieved with MMH fluids can reduce exposure for time-sensitive formations. The MMH system has been applied in drilling high-angle or horizontal wells in Venezuela. Accompanying the increase in the number of directional wells, greater attention is paid to hole cleaning and solids suspension in relation to hole stability. In high-angle wells, the exceptional hole cleaning and cuttings suspension characteristics of the MMH fluid prevent formation of cuttings beds. Washouts are reduced because high annular velocities are not needed. Because this system consistently exhibits a non-damaging nature as a reservoir drilling fluid, it is now more frequently considered as a drill-in fluid for sensitive production zones and for open hole completions. Good filtrate control can be crucial in reservoir sections. Importantly, the MMH filtrate tends to stabilize formation clays, which minimizes swelling and fines migration. Several different types of filtrate control agents are used in MMH systems, and using the most effective products in this regard is seen as the key to success in production zones. The MMH flow profile and fluid structure limit whole mud invasion. In addition, MMH systems are easily displaced by production fluids, allowing rapid and complete clean up. Each of these attributes adds to MMH's production zone performance.

MMH systems are also used for hole stability in mechanically weak or poorly consolidated formations. The flow profile in the annulus, along with the lower pump rates used, result in a stationary layer of fluid along the sides of the hole. Weak rock or sand formations are therefore protected from erosion caused by mud flow. Another benefit of this effect is in contributing to a reduction in seepage losses. This mud loss reduction can be of increased value in production zones. Problem shale can contain both natural and drilling-induced fractures. Most fluid types invade, raising pressure in fractures, leading to wellbore collapse. The MMH fluid offers a mechanically-based stabilization with its unique structure and flow profile, and can minimize this effect, helping stabilize fractured and micro fractured shale zones. Another important aspect of the MMH systems is minimal environmental impact. MMH systems exhibit very low toxicity to organisms, and have small concentrations of organic material. Disposal costs are therefore minimized.

(b) Use of invert emulsions: Donald et.al (2002) put it that an invert emulsions is the most desirable system to choose if economic and environmental concerns allow. It is much easier to prevent washout of the salt section with an oil-based (OBM) or synthetic-based fluid (SBM). Corrosion problems will be minimized with the non-aqueous system and you will have a fluid with maximum lubricity attributes compared to a water-base-mud (WBM). The SBM will provide the most inhibitive system for drilling the rubble zone, but lost circulation is a major issue. Controlled drilling with a fluid containing correct quantities and types of lost circulation materials (LCM) will be required through the rubble zone. Wellbore pressure should be managed to minimize Equivalent Circulating Densities (ECD’s) through these sections commensurate with hole cleaning hydraulic requirements. Water-based fluids should be near saturation to prevent severe washout. Use either sodium chloride for drilling halite or anhydrite sequences in the Gulf of Mexico, or a mixture of magnesium chloride and potassium chloride salts for drilling mixed salt formations in the North Sea. Salt inhibitors have been used to prevent recrystallization of salts on the drill floor but still keep the fluid from falling below saturation downhole. Based on information obtained in this study, such use of inhibitors may not be necessary if drilling with sodium chloride rather than the other chloride. Also, preventing washouts should be planned ahead of drilling the well. In the field, if washouts are suspected then mud inhibition should be increased, lifting capacity of mud improved by increasing the mud yield point (YP) and annular velocities reduced to the absolute minimum consistent with effective hole cleaning.

(c) Use of gravel packs: In preventing washouts by gravel packing, patentopedia states that this invention is directed to a method for controlling sand production in an unconsolidated or loosely consolidated oil or hydrocarbonaceous fluid containing formation or reservoir which is penetrated by at least one wellbore. A gravel packing operation is conducted so as to prevent caving of a washed-out area around said wellbore. Once the gravel packing sand has been placed into the caved out area adjacent the wellbore in the formation, calcium silicate cement is formed in-situ so as to reduce the permeability of the gravel pack sand while consolidating said pack and area substantially near the wellbore.

In the practice of this invention, an alkali metal silicate solution is injected into an interval of the formation containing the gravel pack sand. The alkali metal silicate enters the interval through perforations made in a cased well penetrating the formation. By increasing the viscosity of the silicate or by use of a mechanical packer, penetration of the fluid into the interval can be controlled. As the alkali metal silicate enters the interval, it saturates said interval. After a desired volume of silicate has been placed into the interval requiring sand control, an alcoholic solution of hydrated calcium chloride is next injected into the interval. Upon coming into contact with the alkali metal silicate solution which has saturated the interval, calcium chloride reacts with the alkali metal silicate to form calcium silicate cement in-situ. The calcium silicate cement which is formed is stable at high pHs and temperatures in excess of about 400.degree. F. These steps can be repeated until the permeability of the gravel pack sand has been reduced to the extent desired to control fines migration. Reduction of the permeability continues until a pore size is obtained which is sufficient to prevent formation fines or sands from migrating from the interval into the wellbore during the production of hydrocarbonaceous fluids. Thereafter, production is commenced and substantially fines free hydrocarbonaceous fluids are produced to the surface. By controlling the strength and rate of injection of the alkali metal silicate and the calcium chloride which are injected into the interval being treated, the permeability, porosity and consolidation strength of the gravel pack sand and formation can be tailored as desired.

It is therefore an object of this invention to provide for an in-situ calcium silicate composition for reducing the permeability in an interval of a formation containing gravel pack sand so as to obtain porosity sufficient to exclude fines and sand from produced hydrocarbonaceous fluids which composition is more natural to a formation's environment. It is another object of this invention to provide for a composition which will ensure an even flow front, a homogeneous consolidation and uniform porosity so as to substantially exclude the entry of formation fines and sand into a wellbore from an interval treated with said composition.

It is yet another object of this invention to consolidate an unconsolidated or loosely consolidated interval in a formation containing gravel pack sand while obtaining porosity sufficient to exclude formation fines or sand. It is a still yet further object of this invention to provide for a method to obtain a desired porosity within an interval of a formation containing gravel pack sand which can be reversed by treating the interval with a strong acid.

It is an even still yet further object of this invention to provide for a formation consolidation and porosity reduction agent which is resistant to water, high temperatures and high pH's.

It is yet an even still further object of this invention to provide for a consolidation and porosity reducing composition lacking a particulate matter therein which matter might prevent penetration of the composition in an area requiring consolidation, flow alteration, or pore size reduction.

2.2 Cuttings Accumulation in Washouts

The fact that cuttings tend to settle on low side of inclined wells, the reason and some indicators of cuttings accumulations is considered in this section. Focus will also be place on following: cutting accumulation in cavities, removal of cuttings from well, guidelines used in deviated wellbore during cuttings removal in washout, and comparison of published research done on cuttings removal in washout.

2.2.1 Cutting Accumulation in Cavities

Infohost (2012) revealed that accumulation of cuttings can occur in wells that do have adequate hole cleaning. This is common directional or horizontal wells. Increasing circulating pressure while drilling, or increase in drag pipe causes/363-mechanical-sticking-cause-of stuck-pipe. (html), it is noted that cuttings accumulation is indicated by:

- Reduced cutting on the shale shaker
- Increased over pull
- Loss of circulation
- Increase in pump pressure without changing any mud properties.
- While drilling with a mud motor, cutting cannot be effectively removed due to no pipe rotation.

- Drilling with high angle well (from 35 degrees up).
- Abnormality in torque and drag with the help of a trend (increase in torque/drag).

As a remedy, the publication of the New Mexico Institute of Mining and Technology: Science Engineering Research University posited that in order to minimize the effects of cuttings accumulation, we generally do the following:

- Ensure proper drilling hydraulics, rate and viscosity.
- High rotation rate in directional holes.

The main cause of borehole caving is lack of suitable drilling mud. This often occurs in sandy soil where drillers are not using good bentonite or polymer. The problems can be seen when fluid is circulating but cuttings are not been carried out of the hole. If you continue to push ahead and drill, the bit can become jammed, the hole will collapse when you try to insert the casing or the huge portion of the aquifer may wash out making it very difficult to complete a good well. The solution is to get some bentonite or polymer or, if necessary, assess the suitability of natural clay for use as drill mud. Borehole caving can also occur if the fluid level in the borehole drops significantly Therefore, following a loss of circulation or a night time stoppage, slowly re-fill the borehole by circulating drilling fluid through the drill pipe (pouring fluid directly into the borehole may trigger caving). If caving occurs while drilling, check if cuttings are still exiting the well. If they are, stop drilling and circulate drilling fluid for a while.

Sometimes part of the borehole caves while the casing is being installed, preventing it from being inserted to the full depth of the borehole. When this occur the casing must be pulled out and the well re-drilled, with heavier drilling fluid. When pulling the casing, no more than 12.19 m (40 ft) should be lifted into the air at any time; more than this will cause thin-walled (Schedule 40) PVC to bend and crack.

2.2.2 Guidelines Used In Deviated Wellbore During Cuttings Removal in Washout

Given the considerations of deviated wells, the present practice in the industry to cure the "cuttings bed" problems in "horizontal" wells is to perform "wiper trips". For a "wiper trip" the drill string is pulled back along the well, pulling the bit through the horizontal section of the well. Dragging the bit stirs up cuttings from any "bed" and permits the drilling fluid to transport the cuttings up the well. However, dragging the bit can damage its gauge side and dragging the bit while rotating further reams the hole. And although wiper trips can cure a "cuttings bed" problem, they are expensive in the time and equipment they consume. In some wells wiper trips can consume 50% or more of the time of drilling.

The use of muds with special viscosifiers is also practiced in the industry to enhance a "cuttings transport" characteristic of a drilling fluid. However, even with specially viscosified drilling fluids, cuttings still settle to form a "cuttings bed" in horizontal wells drilled with a downhole motor. Wiper trips are still required. Thus, although improving the cuttings carrying characteristics of a drilling fluid can delay the settling rate of cuttings, it will not eliminate a cuttings bed from forming in time.

To add a further complicating factor, the use of such special viscosifiers may not always be possible. Horizontal drilling may be performed "under-balanced". Although drilling is typically performed "over-balanced," where a drilling fluid is selected such that the hydrostatic head from the fluid "over-balances" the pressures expected from any downhole formations, "under-balanced" drilling is a growing practice particularly in horizontal wells because it can be less damaging to sensitive formations. In "under-balanced" drilling the hydrostatic head of the drilling fluid is designed to be exceeded by the pressures expected from the formations downhole. Under-balanced drilling is typically achieved by adding a gas such as nitrogen to a drilling fluid such as water. Drilling under "under-balanced" conditions further limits the ability to maximize a cuttings transport characteristic of a drilling fluid by adding viscosifiers.

Pulling a drill string for a wiper trip typically does not proceed at a rate greater than fifty feet per minute, and usually proceeds slower. Also further time is consumed with wiper trips in returning the string to the drilling position. Hence, removing cuttings using a critical-level-of-flow method offers the promise of saving valuable time. Further, using a critical-level-of-flow method offers the advantage of avoiding wear and tear on the drill string and bit occasioned by pulling in and out with wiper trips, and offers the advantage of not reducing further the lifetime of the coiled tubing by reeling it in and out in a wiper trip, at whatever differential pressure.

Indications are that a "critical level" of flow for drilling fluid in a horizontal well typically occurs at a rate of 3 to 5 feet-per-second. Such a flow rate raises three problems which the instant invention addresses. This critical level of flow is frequently above the maximum flow rate prescribed for fluid flow through a downhole motor. Establishing the critical level of flow may exceed the capacity of the drilling fluid pump.

Studies indicate that if fluids of either the same composition as the drilling fluid or of an alternative composition are pumped in a deviated or horizontal portion of a wellbore at least 120 % of the fluid flow rate typically used for drilling, such pumping produces wellbore flow rates at a "critical" level. Such flow rates result in a comparatively rapid removal of "cuttings beds" from a horizontal wellbore, especially if drilling is discontinued and no new cuttings are being created. Not only can "cuttings beds" thereby be removed without wiper trips but also the rate of removal of the beds can exceed that of wiper trips, e.g. approximate a linear foot a second. Studies indicate that increasing the flow rate of fluid into the wellbore from 20 % to 50 % of the normal drilling flow rate will increase the rate of removal of cuttings beds from 2 fold to 4 fold.

In summary, the following are the practical hole cleaning guidelines used in the field:

Listed below are practical hole-cleaning guidelines aimed at field use on directional bores.
Use hole-cleaning techniques to minimize cuttings-bed formation and subsequent slumping which can occur in 30-60 degree hole sections.

- Utilize elevated-viscosity fluids from the start because cuttings beds are easy to deposit but difficult to remove.
- Maintain LSRV between 1.0 and 1.2 times the hole diameter when in laminar flow. This requirement will be easier to accomplish if the fluid is treated with a super's or high vis. This product is a bio-polymer that elevates the LSRV in fluids.
- Treat mud to obtain elevated, flat gels for suspension during static and low flow rate periods. Consider using the mud system that will give you excellent LSRV values and superior suspension abilities. The system uses an untreated bentonite and a mixed metal hydroxide additive.
- Schedule periodic wiper trips and pipe rotation intervals for situations where sliding operations are extensive.
- Rotate pipe at speeds above about 50 RPM if possible to prevent bed formations and to help remove pre-existing beds.
- Expect little help from viscous sweeps, unless they are accompanied by high flow rates and pipe rotation.

2.2.3 Summary/Comparison of Published Research Done on Cuttings Removal in Cavities during Washout

Table 2.1 lists some typical experimental researches on cutting removal in washout. The Table indicates fluid flow rate, mud rheology, inclination, pipe rotation, ROP, particle size, pipe eccentricity, mud density have a certain effect on cuttings transport, and multi-factor interactions also were observed.

Table 2.1: Experimental analysis of major factors that promote cuttings accumulation in cavities.

Experimental facility	Key parameters	Additional parameters	References (source)	Conclusions
BJ service	Fluid flow		Li *et al.(1999)*	The carrying capacity increases dramatically for flow rate larger than critical cuttings transport velocity.
UTDRP	Mud rheology	Flow pattern	Okrajni *et al.(1986)*	In laminar flow, higher mud yield values and YP/PV provide better cuttings transport. Cuttings transport was not affected by mud rheology in turbulent flow.
		Drillpipe rotation	Saasen *et al (1998)*	Pipe rotation leads to more efficient cuttings transport for gel structure cuttings bed.
BJ Services		Inclination	Li *et al.(1999)*	Hole cleaning is more efficient with a low viscosity fluid in turbulent flow for horizontal / near horizontal wellbore, or with a high viscosity fluid in laminar flow

Experimental facility	**Key parameters**	**Additional parameters**	**References (source)**	**Conclusions**
				for the vertical/near vertical wellbore
Heriot-Watt University	Inclination		Peden *et al.(1990)*	Hole cleaning is more efficient with a low viscosity fluid in turbulent flow for Horizontal / near horizontal wellbore, or with a high viscosity fluid in laminar flow for the vertical / near vertical wellbore
UTDRP			Okrajni *et al (1986)*	Cuttings are harder to be transported at 45°-55° angle.
BP Research Centre			Brown *et al.* (1989)	The poorest removal rates generally occur with angles in the region of 50 to 60 degrees.
Heriot-Watt University	Drillpipe rotation	Fluid viscosity and velocity, eccentricity, and hole size	Peden *et al. (1990)*	Pipe rotation has a significant effect on the minimum fluid velocity in medium or highly viscous fluids. MTV was reduced in the +50% eccentricity but there were no noticeable effects of pipe rotation in -50% eccentricity. In small annuli, good hole cleaning can be obtained.
Southwest Research		Inclination, particle size, ROP	Sifferman *et al. (1992)*	Pipe rotation has the greatest effect on hole cleaning at inclination near horizontal, for small cuttings, and low ROP.
UTDRP		Motion manner, flow rate and inclination	Sanchez *et al (1999)*	Orbital motion can efficiently improve hole cleaning. At 90 degrees and low flow rates high rotary speed produce the most benefits. Higher rotary speeds are better in lower inclinations
	Pressure drop		Saasen *et al. (1998)*	Cuttings bed height is reduced when the frictional pressure drop is increased.
BJ Services	ROP		Li *et al. (1999)*	Increasing ROP results in the higher bed height for fixed liquid flow rate. For a given ROP, higher fluid flow rate results in a lower and bed height
University of petroleum	Mud density		Wang *et al.* (1995)	Cuttings bed height and critical cuttings transport velocity decrease with the increase in mud density.
UTDRP	Particle size	Size from 2 to 7 mm	Bassal (1995)	Smaller cuttings are slightly harder to clean out.
Petrobras		Size from 2 to 6 mm	Martins *et al. (1996)*	Larger particles are always harder to be transported than smaller ones
UTDRP		Size from 2 to 7 mm	Sanchez *et al (1999)*	At high rotary speed and with high viscosity mud, the smaller cuttings are easier to transport.
Heriot-Watt University		Size from 1.7 to 3.35 mm	Peden *et al. (1990)*	Smaller cuttings were more difficult to transport at all angles of deviation with low viscosity fluid. While larger cuttings were easier to transport at low angles (from 0° to 50°) with high viscosity fluid.
BJ Services	Pipe eccentricity	Inclination	Okrajni *et al. (1986)*	Solids transport is affected slightly by eccentricity at low angles, but as the inclination angle is increased the effect becomes significant in laminar flow.
University of Petroleum			Wang *et al. (1995)*	Cuttings concentration increases as the eccentricity is increased. Pipe eccentricity makes critical annular velocity increase.

2.3 Detection of Downhole Washouts through Surface Parameters during Tripping Operations

To really have a clear understanding of how surface parameters during tripping operation can be used to detect downhole washout, we need to go stepwise ahead: How to detect washout in wellbore, Key Indicators Washout Development in Wellbores, Downhole Problems and Restrictions Associated with Washout.

2.3.1 How to Detect Washout in Wellbores

(a) Use of lag time: First, washouts can be determined exactly by their effect on the lag time. A washout creates a larger annular volume that requires more pump strokes to circulate from the hole. Therefore, if the actual lag time is greater than the calculated time, a washout exists. This may be determined from actual lag checks, from gas responses due to formation change or connection gas, etc. Another indication of the hole washing out may be an increased volume of cuttings.

(b) Use of caliper log: A publication by geobib indicates that the caliper log measures the diameter in the borehole for each specific level and is therefore useful to detect washouts. Washouts occur when the formation is loose or unconsolidated and the drilling mud flushes away parts of the formation. The mud can also invade the formation to various depths depending on the consolidation of the unit, which can therefore, affect the formations physical properties. In line with this, Donald et.al (2002) said it is strongly recommended that an acoustic caliper be run to ensure the degree of washout is known in any borehole where drilling with under-saturated brine was tried.

Below are other views of two authors on how washouts in wellbores can be detected.

According to Gochioco and Magill (2002), the best and most modern way to detect washouts is by using a borehole camera, in their paper titled: *"The borehole camera: An investigative geophysical tool applied to Engineering, Environmental and Mining challenges"*

Drilling is the litmus test to confirm interpretations made on various scientific data sets applied to petroleum, mining, engineering, and environmental challenges. However, traditional drilling and logging techniques can yield residual inconclusive data for rational assessment because small fractures, washout and thinly laminated layers, minor casing damage, etc., may be too small for standard logging tools to detect. To close this uncertainty gab, borehole camera (BHC) systems can be employed to enhance the investigation and inspection of shallow holes. The capabilities of this simple optical imaging tool have, until now, remained unutilized. Technological advances in electronic component design and sensing devices in the last decade have enabled the development of cost-effective BHC unit can operate in both wet and dry conditions. The slim-line design allows the BHC to easily operate in small diameter holes commonly used in near surface exploration and assessment studies. A videocassette recorder attached to the BHC records entire survey. The videotape can subsequently be played back in the office for those who were not at the well site to examine the survey results. Real-time video inspection of open and cased wells can be used to determine the success of drilling operations and can also show images of potential problem areas. In some cases, the recorded video tape has served as evidence in court where survey results quickly resolved litigation, thus saving time and money. Unconsolidated rock layers usually create unstable conditions in the borehole because loose rocks could separate from the wall, subsequently filling and clogging the hole. In cases like the washout condition in Figure 2.2a and 2.2b, a BHC survey would normally indicate the need to install such a casing to keep the hole open to support certain operations such as ventilation, dewatering or other purposes".

Fig.2.2a: Unconsolidated rock layers from a borehole.

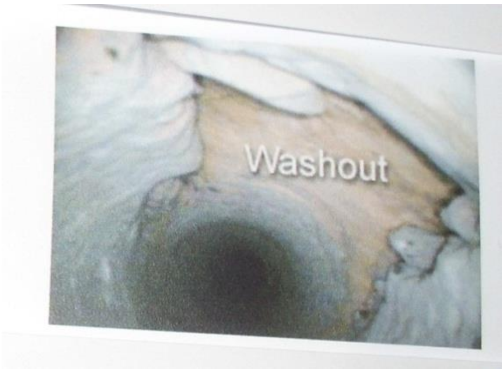

Fig.2.2b Washout condition (Gochioco et al. 2002)

Other methods of detecting washouts in wellbores are:

- Irradiating the earth information in the vicinity of the borehole with fast neutrons from a relatively high intensity neutron source;
- Detecting essentially only the epithermal neutron population at a first shorter spaced from said source in borehole;
- Detecting essentially only the epithermal neutron population at a second longer spaced distance from said source in the borehole;
- Discriminating against the detection of the thermal neutron population at said detectors in the borehole;
- Combining the epithermal neutron population measurements made at said two different spaced distances by taking a ratio of said epithermal neutron population measurements to derive a first, compensated, indication of formation porosity;

- Deriving a second, uncompensated, indication of formation porosity from said measurement of the epithermal neutron population at said shorter spaced distance alone; and
- Comparing said compensated and said uncompensated porosity indications by deriving a percentage compensation parameter C to locate the presence of borehole washouts or cements voids.

It is however necessary to state here that the above cited research works has not addressed the cause of washout and their potential consequences of tripping through them as well as cuttings bed height in washout, hence this research work is committed to making this findings and this would make it different from the above referred research work.

3. Model of Washout Problem

Modelling is part of a solution of an engineering problem that aims at producing mathematical description. This can be obtained by taking advantage of the known laws of physics. These laws cannot be directly applied to the real system. It is necessary to introduce many assumptions that simplify the problem to such an extent that the physics laws may be applicable. This part of modelling is called creation of the physical understanding. In this section, physical and mathematical modelling of washout would be presented.

When real fluids flow through pipes, frictional forces are exerted on the fluid by the walls of the pipe as well as viscous forces within the fluid. The fluid layers next to the walls of the pipe "stick" slightly to the pipe. As you move further from the walls towards the centre of the fluid, this boundary layer ends and the fluid moves faster and more coherently. Viscous forces within the fluid produce a shearing action that results in tiny layers of fluid of ever-increasing speed which eventually reach the speed of the free stream in the centre of the pipe. Energy is lost within the fluid to both of these forces.

3.1 Physical Model of Effects of Tripping Through Washouts

A physical model is a system whose operation can be used to predict the characteristics of a similar system, or prototype, usually more complex, or built to a much larger scale. A model is a scaled version of the real construction. It is believed that the model is always smaller, but not always true. For example if we want to make a very small computer chip to illustrate its function properly, the model is made bigger as compared to the original. In this case, the dimensions of the annulus used for modelling cuttings accumulation in washouts and the behaviour of the cuttings as the BHA is pulled through, it may either be too small or too large for a typical washout scenario.

As shown in Figure 3.1, cutting may get trapped in oversize areas, known as washouts, on their way to the surface. In these enlarged areas, the velocity of the drilling fluid slows. This may cause the slip velocity is constant, but the time of passing is larger than the fluid velocity, and the cutting will settle in the washout area. These cuttings can build up until they fall back into the fluid path and appear at the surface as slugs of cuttings (intermittent or erratic returns).

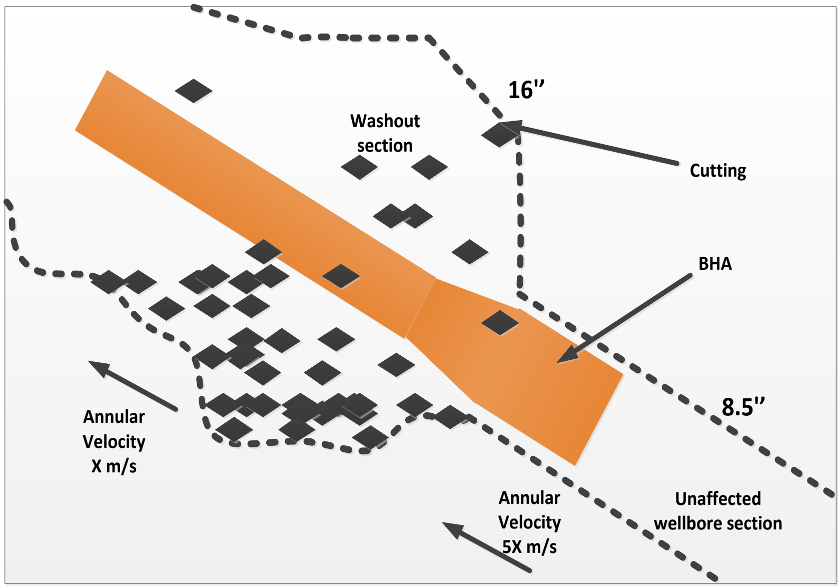

Figure 3.1: Illustration of washout effects on hole cleaning

The effect can be visualized by comparing it with a river running through a wide valley at a rate of, say, 10,000 gallons per minute. Where the valley is wide, the river flows more slowly. However, when the valley narrows, and the river flows through a narrow gorge, the flow rate remains the same, but the speed must increase, since the same amount of water has to flow through the narrow gap. This gives rise to turbulent flow, seen as the presence of rapids.

This can be applied to the wellbore. The annulus between the BHA and the wellbore is the gorge, where the speed of flow is high. The annulus between the drillpipe and the wellbore is the wide valley, where the speed of flow is lower, and the washed out sections of the bore are similar to lakes where the speed is very slow.

3.2 The Model

The wellbore is made up of three sections. Two sections are of the same diameter, while the section at the middle representing the washout has a diameter greater than the other two sections. All three sections are joined together. The model is used in horizontal position to simplify the operation. This is representative of the best case for hole cleaning, as no avalanching will occur.
The model is operated with no fluid or fluid flow. A fluidized bed would flow more readily than a dry bed. Obviously, a dry bed is not the case in reality, but, although the distances, forces and times may vary, the mechanics of the operation do not change greatly. The model is sufficient for illustrating the basic principles of what happened downhole when pulling out without back reaming or circulating.

Figure 3.2 shows the cross section of the bit model, clearly illustrating the flow by area.

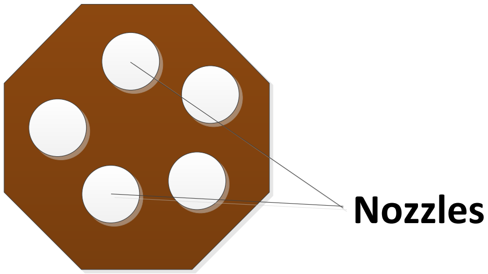

Figure 3.2: Bit model showing the flow area (nozzles)

The lower section of the BHA can be seen prior to entering the annulus as depicted in figure 3.3. The stabilizer and bit are clearly visible.

Figure 3.3: Stabilizer and bit used in the model

The drillpipe/Collar crossover is shown 'shovelling' a substantial pile of cuttings ahead of the change in cross sectional area.

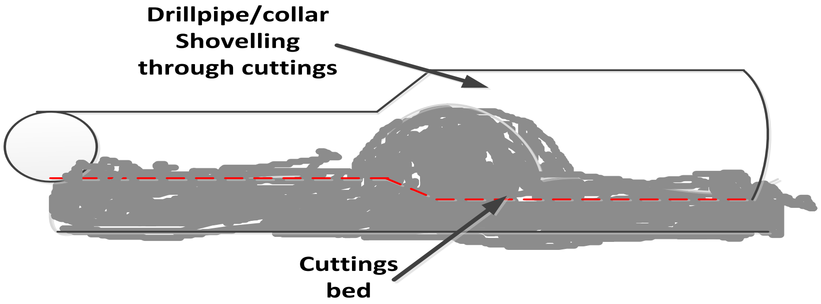

Figure 3.4: The drillpipe/collar shovelling through the cuttings bed

After pulling the BHA a foot further into the model, a pile of cuttings ahead of the drillpipe/collar can be seen to increase in height.

The top stabilizer enters the tube and cuttings begin to build up. As the BHA is drawn further into the wellbore, the cuttings can be seen to build up around the stabilizers.
The straight bladed stabilizer has less of a shovelling effect than the spiral stabilizer. The difference in thickness of the cutting of the cutting bed after the BHA has passed can be seen in the Figure 3.5.

As the BHA is drawn further through the tube, a significant pile cutting builds up in front of both stabilizers. The gap at the top of the annulus had now closed and the stabilizer is effectively packed off with cuttings. The over pulls now increase rapidly and the string will become stuck in a short time.

Here in figure 3.5, an overview of the stabilizers, drillpipe / collar and the cuttings piling up around them can be seen clearly.

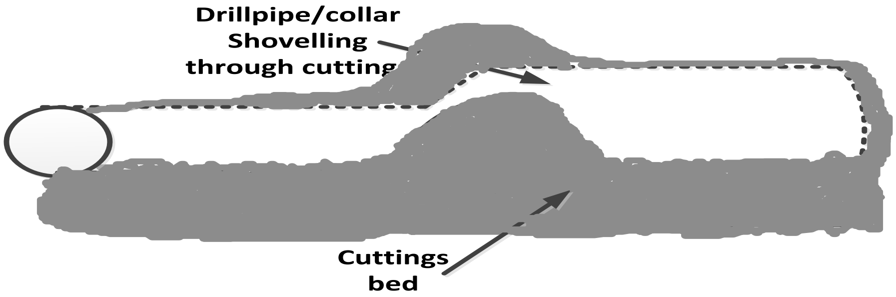

Figure 3.5: The piling up of cuttings on the drillpipe/collar

Figure 3.5 further shows how the cuttings are dragged ahead of the stabilizers, leaving very few behind to cause problems at the bit. If the flow-by area of the stabilizer were not as restrictive, then the piling of the cuttings would occur at the bit. Due to the lower flow-by area of the bit, the piling up of cuttings would occur over a short distance.

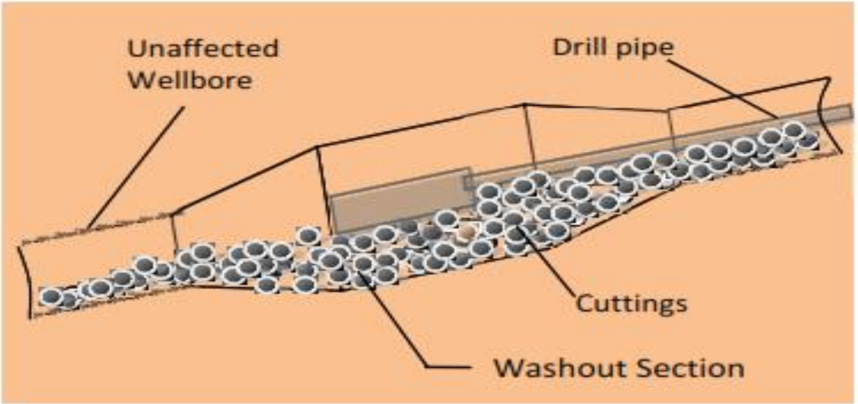

Figure 3.6: Physical model of cuttings accumulation in washout inclined wellbores

Figure 3.6 above shows what happens when the drill pipe is pulled out of a wellbore through washout section. Since cuttings settle in these washouts section due to low velocity of drilling fluids to transport these cuttings out of it, when tripping, the drill pipe with the collar packs these cuttings close to the normal section of the hole. And, this may leads to stuck pipe situations.

There is a bed of cuttings, lying beneath a suspension region. The concentration of cuttings within the suspension region is determined from entrainment of cuttings from the bed, turbulent diffusion, and sedimentation of the cuttings under gravity. We assume that the cuttings bed (if it exists) is of uniform cuttings concentration.

Fluid flow in the suspension region will apply a shear force on the top of the cuttings bed. Since the hole is inclined, then there will be a gravitational force in the opposite direction. These forces will be countered by friction between the cuttings bed and the hole wall. If the friction force is less than a constant multiplied by the normal force, then the cuttings bed will be stationary; if the friction force is greater than this constant multiplied by the normal force, then the cuttings bed will slide: either uphole (due to fluid shear) or downhole (a process known as "avalanching").

3.3 Summary of the physical model

- The model illustrates how the cuttings can build up in front of stabilizers and other changes in cross sectional area.
- It can be seen from the model why jarring up when getting stuck while pulling out of the hole can be wrong thing to do.
- The model is aimed at situations where gauge or close to gauge hole exists. Over gauge hole will give fewer problems with cuttings build up as the flow-by area around the BHA components will effectively be greater.
- The depth of a cutting bed that will cause problems while pulling out of hole is surprisingly small.
- It can also be seen from the model what happens when the drill pipe is pulled out of a wellbore through washout section.

3.4 Hole Washout Model

In light of the model set up in this work and the discussion on the reason of borehole diameter enlargement caused by drilling fluid, it was considered that the probability of arousing borehole diameter enlargement by the fluid shearing stress of drilling fluid itself was small, and its genuine reason was the impact of solid particle′s in drilling fluid against the borehole wall, thus putting forward a borehole diameter enlargement theory of solid particle washout. A physical-mathematical model of impacting against the borehole wall by solid particles was set up and the factors affecting washout result were analysed by solving the model. Through investigation, it was shown that the washing action of the solid particles in drilling fluid against the borehole wall is of selectivity, i.e. it is very weak to the wall rocks with relatively great strength and grains but strong to those with relatively small grains as sandstones and mudstones and the washing action is highly sensitive to grain size and the washout acting force will be exponentially increased along with the decrease in grain diameter of wall rocks. All the conclusions are of great importance to guiding the solid control and pumping rate standards in the operation on the spot.

3.4.1 Mathematical Description of the Model

Model Hypotheses

The following simplifying hypotheses were considered in the development of a mathematical model.

(1) Flow phase and state

- The flow pattern in the annulus shall be in steady state and a two-phase solid-liquid incompressible mixture.

(2) Cuttings

- Cuttings size, sphericity, and distribution were assumed to be uniform.
- Volumetric concentration of drilled cuttings in the upper layer (heterogeneous fluid layer) is assumed negligible.

(3) Carrier fluid

- Ostwald de Waele (Power law) fluid model is considered
- Carrier fluid density and rheological properties were constant.

3.4.2 Model Description

For a qualitative description of the problem, two issues need to be addressed in order to minimize the likelihood of experiencing difficulties associated with tripping through the cuttings beds. First, it is necessary to minimize the height of the cuttings bed that forms while drilling. Second, it is necessary to describe the tendency of the bottom-hole assembly (BHA) to plow the bed and form plugs of cuttings.

The issue of bed height minimization is addressed by the mathematical model that calculates the equilibrium height the cuttings bed. This height is a function of several drilling variables, such as pump flow rate, and drilling fluid density and rheological properties.

However, this model for calculating cuttings bed height in washouts suggests that in a typical bed erosion curve, an increasing amount of solids indicates the period of injection and consequently, accumulation of solids in the annulus while drilling. In sequence, a tall bed is built up. The drilling fluid flow rate is then increased to the desired value for the bed erosion. The amount of solids in the annulus decreases exponentially to a certain residual bed level (or it may go down to zero depending on the drilling fluid properties and flow rate) and it levels off at that value. Therefore an exponential function is the preferred choice to modeling cuttings bed erosion and bed height.

A model can be developed using an exponential non-regression analysis and can be summarized thus:

The rate of cuttings bed erosion in the annulus with time can be given by the following non-linear exponential model:

$$Q = ae^{bH} \qquad (1)$$

Where
Q = mud flow rate in cubic meters per second,
H = height, in meters,
a and b are regression coefficients.

The next step in the regression analysis is to correlate regression coefficients a and b with flow rate and drilling fluid properties. (In this case n and k values are a power law model).

The coefficient b of the flow rate in the exponential function in equation (1) depends on the values obtained for different polymer drilling fluid systems related to the inverse viscosity function, κ. The parameter κ is defined by the ratio of n to k. It represents the inverse of a special viscosity function k_o. The special viscosity function k_o is an approximation of the viscosity of the fluid at test conditions. It is not a real viscosity in the sense that its value can be compared with proper viscosity values. However, an increase in k_o (or a decrease in n/K ratio) represents an increase in viscosity.

Mathematically, a and b can be related to flow rate Q and is derived as follows:

Given (H_1, Q_1), (H_2, Q_2), . . . (H_n, Q_n), best fit $Q = ae^{bH}$ to the data. The variables a and b are the constants of the exponential model. The residual at each data point H is

$$E_i = Q_i - ae^{bH} \qquad (2)$$

The sum of the square of the residuals is

$$S_r = \sum_{i=1}^{n} E_i^2$$

$$= \sum_{i=1}^{n} \left(Q_i - a e^{bH_i} \right)^2 \tag{3}$$

To find the constants a and b of the exponential model, we minimize S_r by differentiating with respect to a and b and equating the resulting equations to zero.

$$\frac{\partial S_r}{\partial a} = \sum_{i=1}^{n} 2\left(Q_i - ae^{bH_i}\right)\left(-e^{bH_i}\right) = 0$$

$$\frac{\partial S_r}{\partial b} = \sum_{i=1}^{n} 2\left(Q_i - ae^{bH_i}\right)\left(-aH_i e^{bH_i}\right) = 0 \tag{4a,b}$$

or

$$-\sum_{i=1}^{n} Q_i e^{bH_i} + a\sum_{i=1}^{n} e^{2bH_i} = 0$$

$$\sum_{i=1}^{n} Q_i H_i e^{bH_i} - a\sum_{i=1}^{n} H_i e^{2bH_i} = 0 \tag{5a,b}$$

Equations (5a) and (5b) are nonlinear in a and b thus not in a closed form to be solved as was the case for linear regression. In general, iterative methods using EXCEL SOLVER would be used to find values of a and b.

However, in this case, from Equation (5a), a can be written explicitly in terms of b as

$$a = \frac{\sum_{i=1}^{n} Q_i e^{bH_i}}{\sum_{i=1}^{n} e^{2bH_i}} \tag{6}$$

Substituting Equation (6) in (5b) gives

$$\sum_{i=1}^{n} Q_i H_i e^{bH_i} - \frac{\sum_{i=1}^{n} Qe^{bH_i}}{\sum_{i=1}^{n} e^{2bH_i}} \sum_{i=1}^{n} H_i e^{2bH_i} = 0 \tag{7}$$

This equation is still a nonlinear equation in b and can be solved best by numerical methods.

Example 3.1

Below is given the height of cuttings bed in a washout as a function of flow rate.

Table 3.1 Cuttings bed height as a function of flow rate used for model

H (m)	0	1	3	5	7	9
$Q(m3/s)$	1.000	0.891	0.708	0.562	0.447	0.355

If the height of the cuttings bed is related to flow rate via an exponential formula $Q = ae^{bH}$, find the value of the regression constants a and b .

Solution

a) The value of b is given by solving the nonlinear Equation (7),

$$f(b) = QH_i e^{bH_i} - \frac{\sum_{i=1}^{n} Q_i e^{bH_i}}{\sum_{i=1}^{n} e^{2bH_i}} \sum_{i=1}^{n} H_i e^{2bH_i} = 0 \tag{8}$$

and then the value of a from Equation (6),

$$a = \frac{\sum_{i=1}^{n} Q_i e^{bH_i}}{\sum_{i=1}^{n} e^{2bH_i}} \tag{9}$$

Equation (8) can be solved for b using EXCEL SOLVER method. To estimate the initial guesses, we assume $b = -0.120$ and $b = -0.110$. We need to check whether these values first bracket the root of $f(b) = 0$. At $b = -0.120$, the table below shows the evaluation of $f(-0.120)$

Table 3.2: Summation value for calculation of constants of model

i	H_i	Q_i	$Q_iH_ie^{bH_i}$	$Q_ie^{bH_i}$	e^{2bH_i}	$H_ie^{2bH_i}$
1	0	1	0.00000	1.00000	1.00000	0.00000
2	1	0.891	0.79205	0.79205	0.78663	0.78663
3	3	0.708	1.4819	0.49395	0.48675	1.4603
4	5	0.562	1.5422	0.30843	0.30119	1.5060
5	7	0.447	1.3508	0.19297	0.18637	1.3046
6	9	0.355	1.0850	0.12056	0.11533	1.0379
$\sum_{i=1}^{6}$			6.2501	2.9062	2.8763	6.0954

From Table 3.2

$$n = 6$$

$$\sum_{i=1}^{6} Q_i H_i e^{-0.120H_i} = 6.2501$$

$$\sum_{i=1}^{6} Q_i e^{-0.120H_i} = 2.9062$$

$$\sum_{i=1}^{6} e^{2(-0.120)H_i} = 2.8763$$

$$\sum_{i=1}^{6} H_i e^{2(-0.120)H_i} = 6.0954$$

$$f(-0.120) = (6.2501) - \frac{2.9062}{2.8763}(6.0954)$$

$$= 0.091357$$

Similarly

$$f(-0.110) = -0.10099$$

Since

$$f(-0.120) \times f(-0.110) < 0,$$

The value of b falls in the bracket of $[-0.120, -0.110]$. The next guess of the root then is

$$b = \frac{-0.120 + (-0.110)}{2}$$

$$= -0.115$$

Continuing with the EXCEL SOLVER method, the root of $f(b) = 0$ is found as $b = -0.11508$. This value of the root was obtained after iterations with an absolute relative approximate error of less than 0.000008%.

From Equation (9), a can be calculated as

$$a = \frac{\sum_{i=1}^{6} Q_i e^{bH_i}}{\sum_{i=1}^{6} e^{2bH_i}}$$

$$= \frac{\begin{array}{c} 1 \times e^{-0.11508(0)} + 0.891 \times e^{-0.11508(1)} + 0.708 \times e^{-0.11508(3)} + \\ 0.562 \times e^{-0.11508(5)} + 0.447 \times e^{-0.11508(7)} + 0.355 \times e^{-0.11508(9)} \end{array}}{\begin{array}{c} e^{2(-0.11508)(0)} + e^{2(-0.11508)(1)} + e^{2(-0.11508)(3)} + \\ e^{2(-0.11508)(5)} + e^{2(-0.11508)(7)} + e^{2(-0.11508)(9)} \end{array}}$$

$$= \frac{2.9373}{2.9378}$$

$$= 0.99983$$

The regression formula is hence given by

$$Q = 0.99983 e^{-0.11508H} \tag{10}$$

Introducing the effects of the inverse viscosity function earlier mentioned, we get that the regression formula for water and other polymeric fluids is as summarized in Table 3.3

Table 3.3: Parameters used for model prediction

Drilling Variables		Case I (Water)	Case II (0.5g HEC)	Case III (1g HEC)	Case IV (2g HEC)
Fluid rheology parameters	Flow behaviour index n	1	0.8	0.6	0.4
	Fluid consistency index k	1	1.5	2	3
	Inverse viscosity function ‘k’	1	0.533	0.3	0.133
Circulation rate	Q (m^3/sec)	0.1-0.6	0.1-0.6	0.1-0.6	0.1-0.6
Regression coefficients	A	0.99	0.99	0.99	0.99
	B	-0.115	-0.061	-0.0345	-0.0153
Cuttings bed height model	$Q = ae^{bH}$	$Q = 0.99e^{-0.115H}$	$Q = 0.99e^{-0.061H}$	$Q = 0.99e^{-0.0345H}$	$Q = 0.99e^{-0.0153H}$

The plot of the model predictions is as shown in Figure 3.7. In the bed erosion prediction model, the bed height decreases exponentially to a certain residual bed level and it levels off at that value. As it is seen from Figure.3.6 cuttings bed erosion occurs at a faster rate as the drilling fluid flow rate increases.

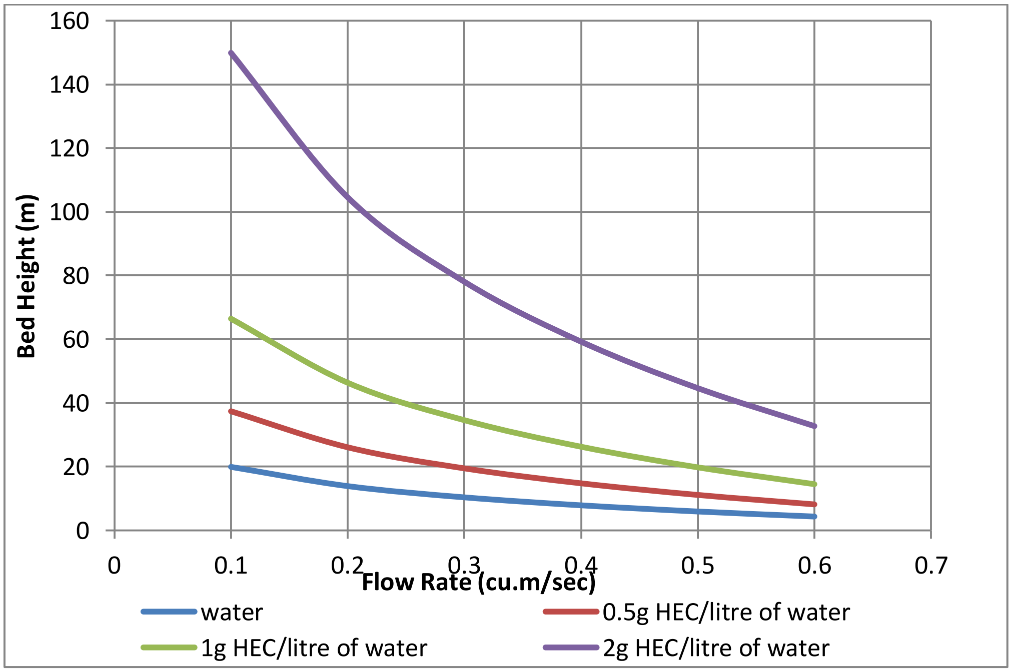

Figure 3.7: Plot of model predictions (bed height against flow rate)

3.4.3 Simplified Program for Estimating Cuttings Bed Height in Washout

Figure 3.8 illustrates a simplified computer program that can be used to predict the stationary cuttings bed height in a washout or any cavity. The program is based on the non-linear regression model used to develop the exponential relationship between fluid flow rate and cuttings bed height.

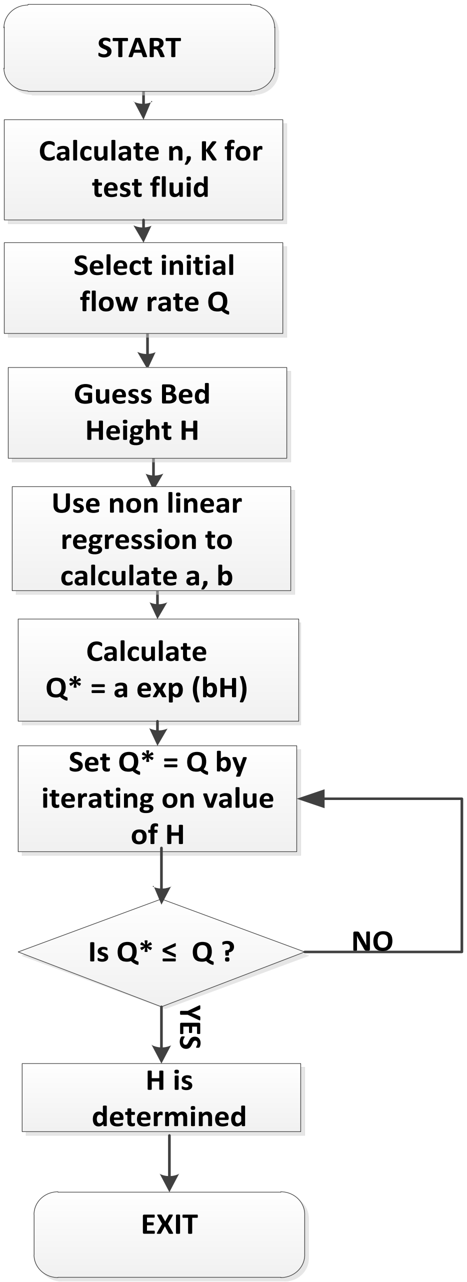

Figure 3.8: Program for prediction of stationary bed height of cuttings

3.4.4 Mathematical Model for Critical Velocity for Rolling and Lifting of Cuttings Models

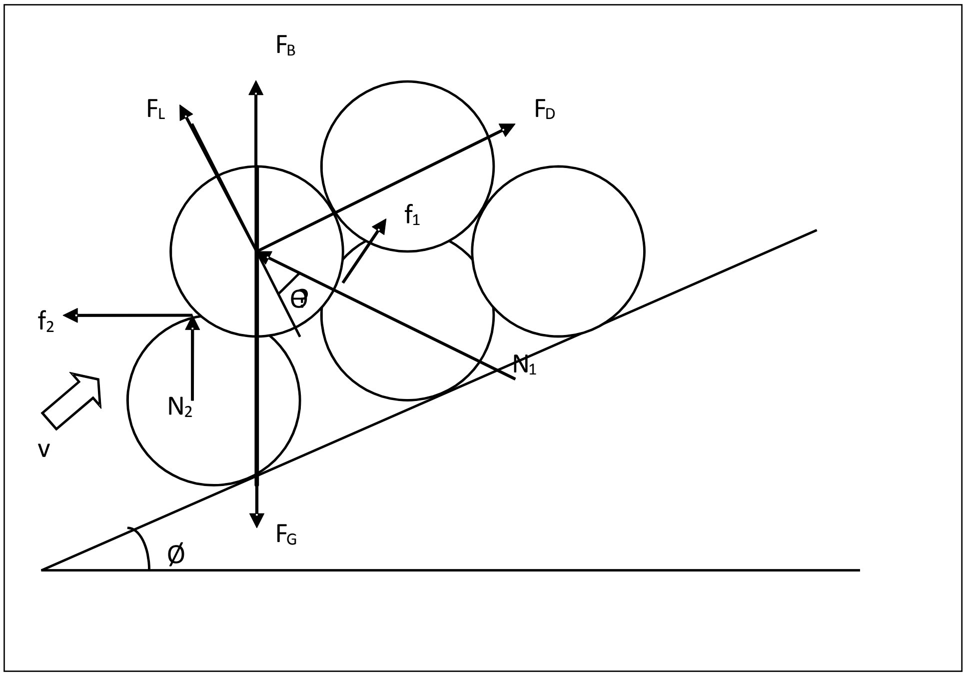

Figure 3.9: Forces acting on a single bed particle

There are several forces acting on a bed particle. These include: drag, lift, buoyancy, and gravitational forces as shown in Figure 3.9, there also normal forces which acts on the bed particle's contact points between the particles as well as frictional forces at the contact points which reduces particle movement.

In order to achieve mathematical simplicity, the following assumptions were made to develop the model:

- Steady state incompressible flow (in other word, the flow is independent on time).
- Cutting particles are uniform and spherical.
- Uniform bed thickness along the annulus.
- Uniform density of the cutting particles.
- No drill pipe rotation.
- Bed particles movement in only two ways: lifting up by the lift forces (hydrodynamic forces) or rolling on the bed surface.

It is pertinent to note that during drilling, the lift force, drag force, and buoyancy force tend to roll the particle downstream from the flow as shown in Figure 3.8, while gravity force tends to prevent the particle from rolling.

Gravity Force (F_G):

$$F_G = \frac{\pi}{6}\rho_p g d_p^3 \ \ldots\ldots\ldots\ldots\ldots\ldots \tag{11}$$

Drag Force (F_D):

$$F_D = \frac{\pi}{8}C_D \rho_l v_p^2 d_p^2 \ \ldots\ldots\ldots\ldots\ldots\ldots \tag{12}$$

Buoyancy Force (F_B):

$$F_B = \frac{\pi}{6}\rho_l g d_p^3 \ \ldots\ldots\ldots\ldots\ldots\ldots \tag{13}$$

Lift Force (F_L):

$$F_L = \frac{1}{8}C_l \rho_l v^2 d_p^2 \ \ldots\ldots\ldots\ldots\ldots\ldots \tag{14}$$

where C_L and C_D are the hydrodynamic lift and drag coefficients respectively.

For rolling of the bed particle to be initiated, the moments of the forces (F_B + F_D + F_L) at a contact point which tends to cause downstream rotation must be exceed the moments of the force F_G that tend to prevent the downstream rotation. Also, the bed particle can be lifted up if the sum of the forces in the forces in the upward direction is greater than those in the downward direction. Therefore, the condition for the initiation of particle rolling at the bed surface is expressed as:

$$F_L R sin\emptyset + F_D R cos\emptyset - (F_G - F_B) R sin(\alpha + \emptyset) = 0 \ \ldots\ldots\ldots\ldots \tag{15}$$

where α = angle of inclination, and
Ø = angle of repose.

The angle of repose, Ø, is defined as the maximum angle of slope measured from the horizontal plane at which cuttings comes to rest on a pile. The moments of the normal and frictional forces are taken to zero, due to fact that when the particle is about to roll, the normal force, N_2 and the friction force, f_2 are zero. In other word, both normal and friction forces are equal during initiation of rolling of bed particle.

The critical velocity for a rolling particle is obtained by substituting force equations into equation above and is expressed as:

$$v_{roll} = \sqrt{\frac{4(\rho_c - \rho_l) g d * sin(\alpha + \emptyset)}{3(\rho_l) sin\emptyset (C_l + C_D)}} \ \ldots\ldots\ldots\ldots\ldots\ldots \tag{16}$$

Similarly, before the particle can be lifted, the friction force and the normal force at contact point must be equal to zero. At the surface of the bed, particle lifting condition is given as:

$$F_L - (F_G - F_B) cos\alpha = 0 \text{ ………………………………………………… } (17)$$

Then, the critical velocity for particle lifting is obtained by substituting force equations into equation (eq. 16), and is expressed as:

$$\mathrm{v}_{\mathrm{lift}} = \sqrt{\frac{4(\rho_l C - \rho_l L) g d cos\alpha}{(3\mathrm{\rho}_{\mathrm{L}} \mathrm{l})\mathrm{CL}}} \text{ …………………………………………….. } (18)$$

These velocities must be taken as the local velocity near the bed surface.

4. Experimental Work

4.1 Aim of the Experiment

The main objective of the experimental work reported here was to investigate the bed height in expansions. This involved finding the stable bed height after long term circulation with cuttings feeding.

4.2 Description of flow loop

The experimental apparatus consists of a long transparent PVC pipe with outer diameter (OD) 0.06 m and internal diameter (ID) 0.0545 m. The flow loop is supported by a structure that can be tilted from horizontal; hence various inclinations from horizontal can be studied. In the loop, the expansion section conveniently referred to as the washout section represented in the schematic diagram was the main area of study. The channel is made of a transparent PVC pipe that is connected at both ends to detachable steel joints of 1.73 m and 3.24 m respectively; the PVC itself is 0.94 m long. The loop is equipped with the necessary measuring equipment such as the flow meter, connected to a personal computer for online display and recording. In order to avoid sand that has been transported from flowing into the channel, a screen was placed inside the pit. The pit also served as a pumping tank for re-circulating the fluid. The temperature was maintained at room temperature. A manual controlled button on the flow meter was used to control the flow rate. The cuttings fed into the test section were 6 000 ml. Figure 4.1a shows the flow diagram of the loop and figure 4.1b show deeply each component of the loop and pictures of these components are display in the appendix. The complete picture of the loop is enclosed here in figure in the appendix.

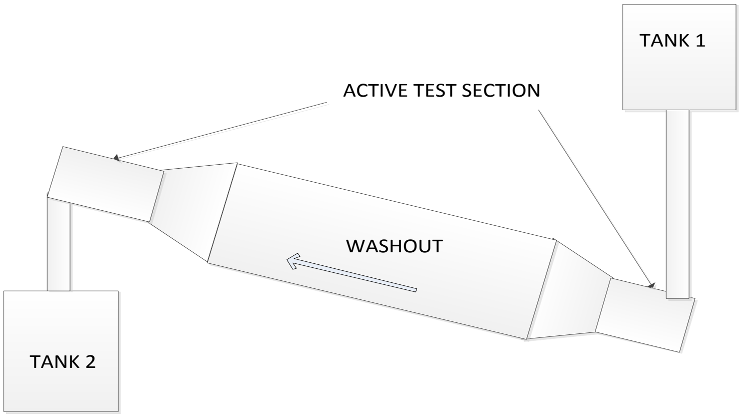

Figure 4.1a: Test loop

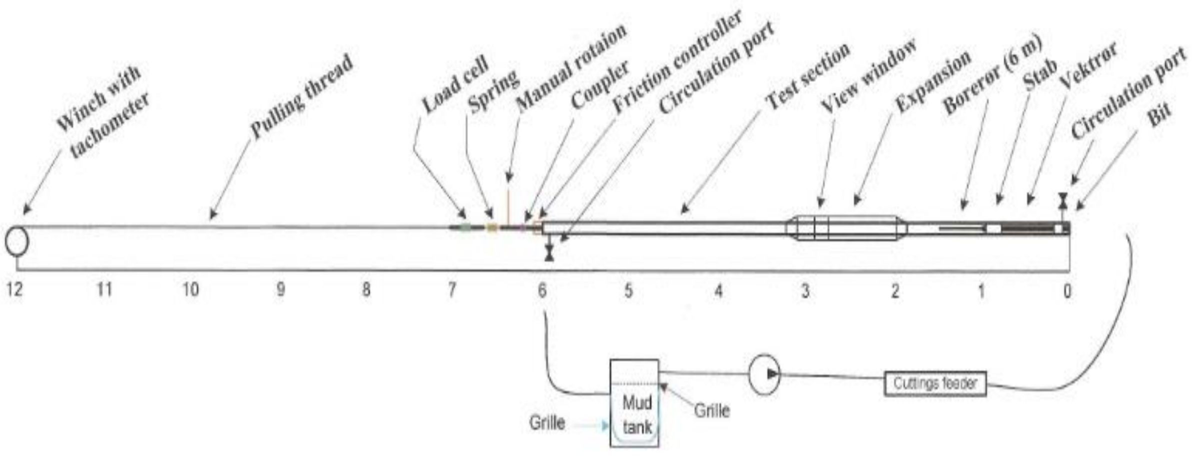

Figure 4.1b Components of the flow loop (Skalle and Uduak 2012).

4.3 Test Apparatus Design

The test apparatus was designed and constructed in accordance with the following requirements: annular-flow steady state conditions must prevail in every test case, and the apparatus must allow the selection of the following variables (flow rate, well inclination, etc.) that must be representative of average field conditions. To meet the above requirements, a test apparatus shown in Figure 4.1 was designed and constructed. It consisted of the following major components: (1) an independent means of circulating the mud; (2) a section of annulus with a washout; (3) a reliable means of controlling of liquid flow rate; (4) a means of varying the angle of inclination of the test section.

4.4 Procedure for Testing

Once the operational parameters (geometry, inclination, fluid and solid properties) are chosen, the following procedure is adopted:

- Fill the test section with 6 000 ml of cuttings to form a bed of constant height along the test section. Fluid flow rate should be minimal and constant;
- Increase fluid flow rate to begin bed erosion. When steady state is reached (no more solids removal), record bed perimeter, transient time and; observe removal flow patterns;
- Repeat the last step, increasing gradually the fluid flow.

4.5 Description of Test Equipment

(a) The Fann V-G Viscometer

The model 800 eight speed electronic viscometer by OFI Testing Equipment Inc. was used to obtain precise measurement of rheological properties of the fluids. Eight precisely regulated test speeds are provided by the OFI pulsed-power electronic speed regulator. The eight speeds are 3 (gel), 6, 30, 60, 100, 200, 300 and 600 RPM. A higher stirring speed is provided and speeds may be changed without stopping the rotor with a control knob selection switch.

Figure 4.2 Fann VG Viscometer

Procedures for Operation

1. Place a fresh sample of drilling fluid in the cup, filling it up to the scribed line inside the cup.
2. Immerse the rotor sleeve exactly to the scribed line by raising the platform and firmly tightening the lock nut on the platform as shown in figure 4.2 above.
3. Rotate the speed selector knob to the stir setting and mix the sample for a few seconds.
4. Rotate the knob to the 600 RPM setting, wait for the dial to reach a steady reading and record the 600 RPM reading.
5. Rotate the speed selector Knob to the 300 RPM setting, wait for the dial to reach a steady reading and record the 300 RPM reading.
6. Rotate the speed selector knob back to the stir setting and re-stir the sample for a few seconds.
7. Rotate the speed selector Knob to the 200 RPM setting, wait for the dial to reach a steady reading and record the 200 RPM reading.

8. Rotate the speed selector Knob to the 100 RPM setting, wait for the dial to reach a steady reading and record the 100 RPM reading.
9. Rotate the speed selector Knob to the 6 RPM setting, wait for the dial to reach a steady reading and record the 6 RPM reading.
10. Rotate the speed selector Knob to the 3 RPM setting, wait for the dial to reach a steady reading and record the 3 RPM reading.

(b) Mixer

In order to obtain an evenly mixed mixture of water and HEC, a mixer was used stir to vigorously, until the desired result was obtained. Figure 4.3 shows an image of the mixer and mixing process of the drilling fluid.

Procedure

1. Ensure that the fan of the mixer is firmly held in place, by using the screw knob available with the mixer for this purpose.
2. Obtain a wide enough container, which will enable the blade on the fan to rotate freely without hitting sides of the container.
3. Pour desired quantity of liquid and substance to be mixed into the container.
4. Ensure that the mixer is properly placed such that the blade is centralized in the container as in the figure 4.3.
5. Connect the mixer to a power source and turn on the mixer
6. Rotate the handle at the rear of the mixer to obtain your desired mixing speed.
7. Allow it to mix, until the desired mixture is obtained.
8. Turn off the mixer and remove from the mixture.

Figure 4.3 Mixer used for the mixing of the drilling fliud

(c) Pump

This section outlines the steps involved in the processes of involved in the controlling of the pump and circulation of cuttings out of the flow-loop.

Procedures:

a. For controlling pump

1. Turn pump button to ON. Notice the green light as the white line on the button is in upward position.
2. Open the control panel of the pump
3. Regulate the pump flow rate
4. Press run: Mud is pumped through the system
5. Press stop: to stop the circulation
6. Close control panel
7. Turn the pump button off

b. For circulation during cuttings transport experiment

1. The mud tank was completely filled with water, since water was used as the drilling fluid.
2. The Prefill test section was filled with 2000 millilitres of cuttings from the rear, while pipe is approximately at an angle of repose.
3. The test section was connected to the circulation system
4. The fluid was pumped (according to the procedure for controlling pump above) until the cuttings formed a stationery bed for the selected pump rate.
5. The time it took to form stationary bed was measured and the bed height and perimeter was also measured.
6. The above procedure was repeated for 6000 millilitres of cuttings.
7. The result obtained was recorded, analysed and compared with result obtained from theoretical studies.

Figure 4.4a: The pump/flow regulator, while in use

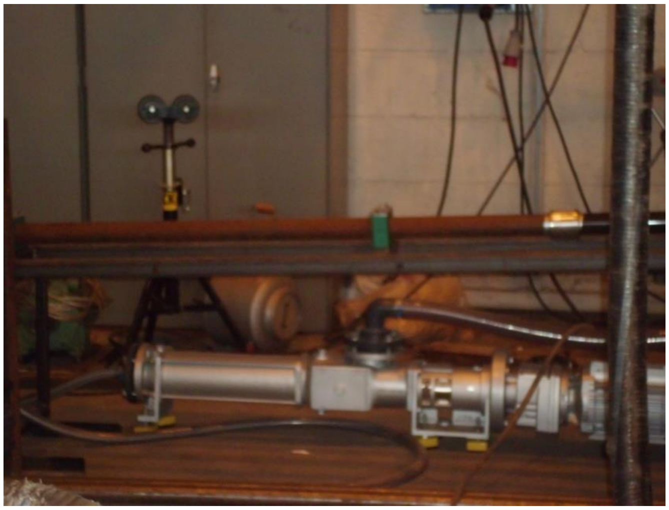

Figure 4.4b: The flow loop setup and the pump

Once the pump is started and circulation is in progress, the cuttings gradually moves from the wellbore to the mud pit.

Pump Calibration

The pump is configured to work in Hertz. Therefore, in order to ensure ease of analysis, it was pertinent that the flow rate is denominated in litres per minute (l/min). Hence a manual calibration was carried for each of the drilling fluid according to the process outlined below:

Manual Calibration Procedures

1. The drilling fluid was mixed to the desired specification (0.0g HEC/1Litre H_2O)
2. The fluid was poured into the mud tank
3. Then the pipe was disconnected from the flow loop and held over a 10 litre container.
4. A stop watch was held in position,
5. The pump speed was set to 5Hz
6. The stop watch and pump was started simultaneously.
7. The time to collect 10 litre of fluid was measured and recorded.
8. The process was repeated for four times and average value was determined and recorded.
9. The procedure 1 to 8 above was repeated for pump speed 10Hz, 15Hz, 20Hz, 25Hz and 30Hz.
10. Then the mud is discarded from the system
11. Procedure 1 to 10 was also repeated above for drilling fluid specifications 0.5g HEC/1Litre H_2O, 1g HEC/1Litre H_2O and 2g HEC/1Litre H_2O respectively.

12. The results were collated and used to determine the flow rate of the pump, the result are as shown in Table 4.1.

Table 4.1: Pump Calibration Result

	Quantity of HEC present in 1 Litre of H_2O			
Frequency (Hz)	**For water**	**For 0.5g HEC/ 1Litre**	**For 1g HEC/ L H_2O**	**For 2g HEC/ L H_2O**
	Flowrate (Litre/min)	Flowrate (Litre/min)	Flowrate (Litre/min)	Flowrate (Litre/min)
5	28.6	26	23.5	13
10	33.3	29.6	26.3	15
15	38.9	34.5	35.9	20.1
20	44.8	41.6	37.5	35.2
25	49.1	42.9	38.7	35.3
30	51.3	50	41.7	37.7

4.6 Experimental Conditions Studied

- **Drilling Fluid Rheology**

The experimental findings reported here were obtained with water and a 0.5g, 1g and 2g HEC drilling fluid for every one (1) litre of water. This mixture is depicted in Figure 4.5. These concentrations were used to provide comparable effective viscosity to that which would be anticipated in a hole section using a field mud. Rheologically, HEC polymer-based drilling fluid behaves as a pseudo plastic fluid. Tables 4.2 and 4.3 shows the results of the rheologies and the characteristics of the fluids used respectively.

Figure 4.5: Mixing HEC in water

Table 4.2: Rheologies of various amounts of HEC in 1 litre of water

		0.5 g HEC			***1g HEC***			***2g HEC***		
RPM	Υ (s^{-1})	Θ	τ (Ib/100ft^2)	τ (Pa)	Θ	τ (Ib/100ft^2)	τ(Pa)	Θ	τ (Ib/100ft^2)	τ(Pa)
600	1022	4	4.24	2.03	6.5	6.89	3.29	7	7.42	3.55
300	511	2.5	2.65	1.27	4.6	4.88	2.33	5	5.3	2.54
200	340	2	2.12	1.02	3.0	3.18	1.52	4	4.24	2.03
100	170	1	1.06	0.51	2	2.12	1.02	3	3.18	1.52
6	10	0.5	0.53	0.25	0.5	0.53	0.25	1	1.06	0.51
3	5.1	0.2	0.21	0.1	0.24	0.25	0.12	0.5	0.53	0.25

Table 4.3 Fluid systems used in comparison

Description	**Base case**	**Fluid A**	**Fluid B**	**Fluid C**
Fluid type	**Water**	**HEC based(thin)**	**HEC based(average)**	**HEC based(thick)**
N	1	0.67	0.497	0.48
k(N-s^n / m^2)	1	0.1	0.105	0.128
Density(kg/L)	1	1.530	1.75	2.68
μ_a (cp) @ 511s^{-1}	1	2.5	4.6	5

4.7 Test Matrix and Input Parameters

In this matrix we have four test sets, every test set contain six test elements that are carried out at different flow rates. A total of seventy two different tests were performed using solutions of Water and HEC. To represent the drilling fluids and particles of sandstone, cuttings of diameters 0.1-2 mm, the fluid flow velocity varies between the minimum limit, which is the critical velocity for a given sand bed, and the maximum limit that is the velocity at which the erosion time is measured visually with acceptable degree of accuracy. The test matrix is shown in Tables 4.4 – 4.7. The cuttings bed height in the tables was presented as dimensionless bed heights. The dimensionless bed height is obtained by dividing the bed height of the cuttings remaining after circulation time by the initial height of the cuttings prior to mud circulation. It must be noted here that the initial value of the cuttings height prior to circulation was 80 mm. The bed height remaining in the washout after circulation can be obtained by multiplying the dimensionless bed heights for the various washout diameters by the cuttings bed height prior to mud circulation.

The following parameters were varied:

- Diameter of washouts: 60 cm, 30 cm and 15 cm

- Flow rates as shown in Table 4.1 were used. Throughout the range of annular velocities studied with HEC the flow regime was laminar and turbulent with water. Detailed photographs taken during the tests are presented in the appendix.

Table 4.4: Test Matrix for water used as the cleaning fluid

	Dimensionless bed height		
Flow rate (l/min)	**With 60cm washout**	**With 30cm washout**	**With 15cm washout**
28.6	0.88	0.81	0.73
33.3	0.75	0.68	0.60
38.9	0.65	0.60	0.55
44.8	0.58	0.50	0.44
49.1	0.47	0.41	0.38
51.3	0.38	0.33	0.21

Table 4.5: Test Matrix for 0.5g HEC in 1 litre of water

	Dimensionless bed height		
Flow rate (l/min)	**With 60cm washout**	**With 30cm washout**	**With 15cm washout**
26	0.94	0.88	0.81
29.6	0.88	0.81	0.75
34.5	0.81	0.70	0.69
41.6	0.73	0.60	0.63
42.9	0.69	0.58	0.50
50	0.58	0.54	0.44

Table 4.6: Test Matrix for 1g HEC in 1 litre of water

	Dimensionless bed height		
Flow rate (l/min)	**With 60cm washout**	**With 30cm washout**	**With 15cm washout**
23.5	0.96	0.95	0.88
26.3	0.93	0.88	0.75
35.9	0.85	0.75	0.69
37.5	0.83	0.70	0.60
38.7	0.80	0.68	0.56
41.7	0.75	0.62	0.48

Table 4.7: Test Matrix for 2 g HEC in 1 litre of water

	Dimensionless bed height		
Flow rate (l/min)	**With 60cm washout**	**With 30cm washout**	**With 15cm washout**
13	0.99	0.98	0.97
15	0.97	0.94	0.93
20.1	0.94	0.90	0.83
35.2	0.91	0.86	0.73
35.3	0.89	0.85	0.71
37.7	0.87	0.80	0.70

4.8 Observations

The scope of these tests was to determine the mechanism of erosion and how long it takes for the cuttings to form a stationary bed height in the washouts with respect to the four fluids used. The tests started with loading the annulus with solids and forming one or two long beds of approximately the same height throughout the annulus section. The erosion test started by increasing gradually the flow rate and through visual observation and video recording the flow rate and mechanism of bed erosion was determined.

- **WATER**

At low flow rates of 28.6 to 38.9 lpm, minimal motion of cuttings in the annulus section, indicating that the liquid is not capable of carrying the solids, thus a high stationary bed pattern exists from 0 to 30 lpm. This is as shown in Figure 4.6

Figure 4.6: Erosion of cuttings with water flow in 15 cm washout

Between 40 and 45lpm, cuttings tend to move a long distances from the entrance of the washout and then they deposit on the bottom forming a stationary bed of cuttings which over time extends over 50% of the initial bed height. This is depicted in Figure 4.7

Figure 4.7: Erosion of cuttings with water flow in 15 cm washout

Above 48 lpm, the cuttings form a continuous moving bed, with the particles on the bottom of the section but moving forward, like soldiers, and moving faster as the flow rate is increased as seen in Figure 4.8 forming a stationary bed of cuttings which over time extends a little over 20% of the initial bed height of cuttings in the annulus.

Figure 4.8: Erosion of cuttings at with water flow in 15 cm washout

The same patterns are observed with water flow in the larger washout diameters. Though the cuttings bed heights are much higher in these washouts due to their depth, the heights decrease as fluid flow rate is increased. Most pictures of the cuttings erosion in washout during the experiment are depicted here in the appendix.

- **HEC MIXTURES**

The flow patterns mentioned above are also observed with the three HEC solutions. The difference is that transitions to the next flow pattern occur at higher flow rates for the more viscous liquids. In addition, the height of the original stationary bed which forms at the low rates is higher and the cuttings move from the entrance of the test section at lower flow rates than with water due to the increased suspension characteristics of the HEC mixtures.

Compared to the case of water flow, a big difference is observed on the erosion mechanism. The particles are now eroded from the top of the bed and not from the front. Furthermore, erosion takes place for almost all but a line of solids of width of one to two particles, which remain in position and are significantly removed only when the flow rate is increased its peak value. It is evident then, that, besides the flow rate, the liquid viscosity plays a role in the erosion mechanism and results in different erosion velocities of the solid bed and this should be taken into account when modelling flow pattern transitions for solid-liquid flows.

4.9 Effects of Cuttings Size on Cuttings Transport

It could be concluded that the particles with small diameters have better cleaning performance compared with the other larger sizes in the washouts. The particles start to move upward to reach the surface at initial low flow rates. The particles with intermediate diameters are transported to the surface when the mud charging is increased to 1.6 times the initial flow rates and the largest particles are transported when the mud discharge is at its peak values. The characteristics of cuttings, such as size, shape and density, are related to their dynamic behavior in a flowing media. The terminal velocity, drag force, buoyancy corrected gravity force and shear forces between cuttings are affected by both the characteristics of the cuttings and the properties of the circulated fluids. The cutting size has moderate effect on cutting transport.

5. Presentation of Results

This section presents a discussion of the input and results obtained in chapter four. The discussion would be divided into two sections namely: (a) Rheology of the fluids used for the test and (b) cuttings bed height in different washout diameters.

5.1 Rheology of the Fluids Used for the Test

Basically, the fluid used for the test was composed of hydroxylethyl cellulose mixed with water in quantities of 0.5 gram, 1gram and 2 grams respectively. In practice, hydroxyl ethyl cellulose behaves as a pseudoplastic fluid. Figure 5.1 shows the rheologies of the different HEC concentration used for the test. It is evident that with the 0.5 grams HEC, its behavior is close to that of water judging from a shear rate of 200 RPM and above. The case is quite different for the 1 gram and 2 grams HEC. These cases really depict the HEC fluid as a true pseudoplastic fluid as seen in the curves in both cases.

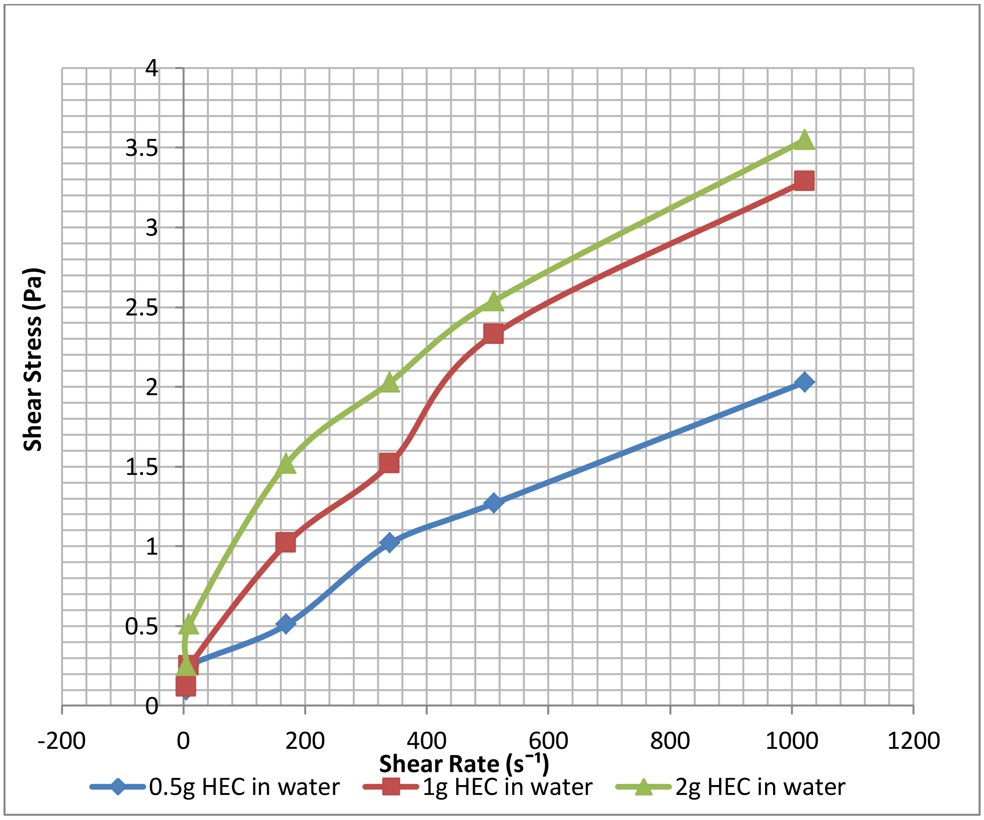

Figure 5.1: Rheology of HEC Fluids used during test

5.2 Cuttings bed height in different washout diameters

In this work, 6 000 ml of cuttings were used in all experiments conducted. Water and aqueous solutions of HEC fluid were used to clean the cutting beds. The HEC fluid was composed of 0.5 gram HEC per litre of water and 1 gram HEC per litre of water. The flow rates ranged from 13 to 50 l/min. Three different washout sections with diameters of 15cm, 30cm and 60cm were used.

For the particular tests reported here, there was no bed erosion at a water flow rate of 13 lpm. As the flow was increased, erosion started on the beds. It was observed that erosion occurred from the front of the bed, where the water or the fluid impinges on the full height of the solid bed. At 51.3 lpm, the flow becomes turbulent and all the cuttings in the washouts are moved into the lean pipe area where they are then moved to the collector tank.

During the flow time for the sand beds, the critical flow velocities could not be determined with some measure of accuracy. As the flow velocity over an initially stationary bed of particles is increased, it was difficult to tell at which point a movement suddenly occurs in the washout section since the flow begins at the unaffected section of the pipe and then emptying itself in the washout section. This is further aggravated by the fact that the diameter of the washout region was so large that it was difficult knowing which area of the bed was moving at a given point in time.

There is however a condition in which a particle leaves the bed. This may be caused by the unstable initial positions of the sand particles. As the flow rate is increased, the particle movement becomes more energized to move until it covers all areas of the bed. Another factor causing the irregular movement of particles is the turbulence caused by increased flow rates and the sizes of the particles. While the smaller particles move faster on increasing the flow rate, the larger particles tend to be left sorted out. At very turbulent conditions, the larger particles join the flow. Thus, although flow is more turbulent above the bed in the washout region, erosion with fluid is observed to occur first from the front of the bed, as depicted in figure 5.2 and figure 5.3.

However, it was observed that the flow becomes more turbulent at the expansion resulting in packing off and erosion of the cuttings. The turbulent effect begins to die off when the flow was gradually ceasing. Nevertheless, this varies upon the different flow rate and viscosity of the fluid that was considered in this work.

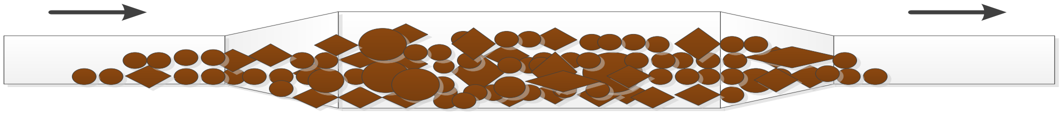

Figure 5.2: Cuttings level before the flow of the drilling fluid

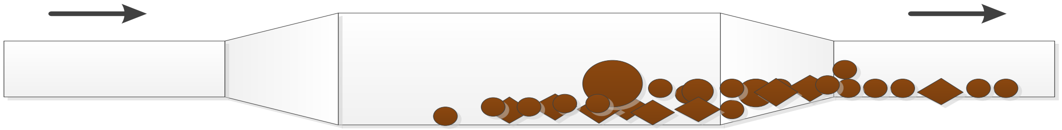

Figure 5.3: Cuttings level after the flow of the drilling fluid

The cuttings bed height left in the washout section of the test apparatus after there are no more cuttings movement is recorded as the residual cuttings bed height. The cuttings bed height results obtained is graphically represented in Figures 5.4 to 5.6.

(i) Cuttings bed height in 15 cm washout

From figure 5.4, the data points loosely define a power law relationship between the flow rate and cuttings bed height. In the case of water, we observe a constant decline in cuttings bed height as flow rate increases. The situation is quite similar to the 0.5 gram HEC case. But the scenario is totally different in the case of the fluid with 2 grams HEC. We see minimal fall in cuttings bed height for almost all flow rates considered. In relation to the bed height of cuttings in the washout, it is seen that water and the 0.5g HEC fluid in water performed better in cleaning the cutting bed especially at high flow rates judging from the low values of the cuttings bed height.

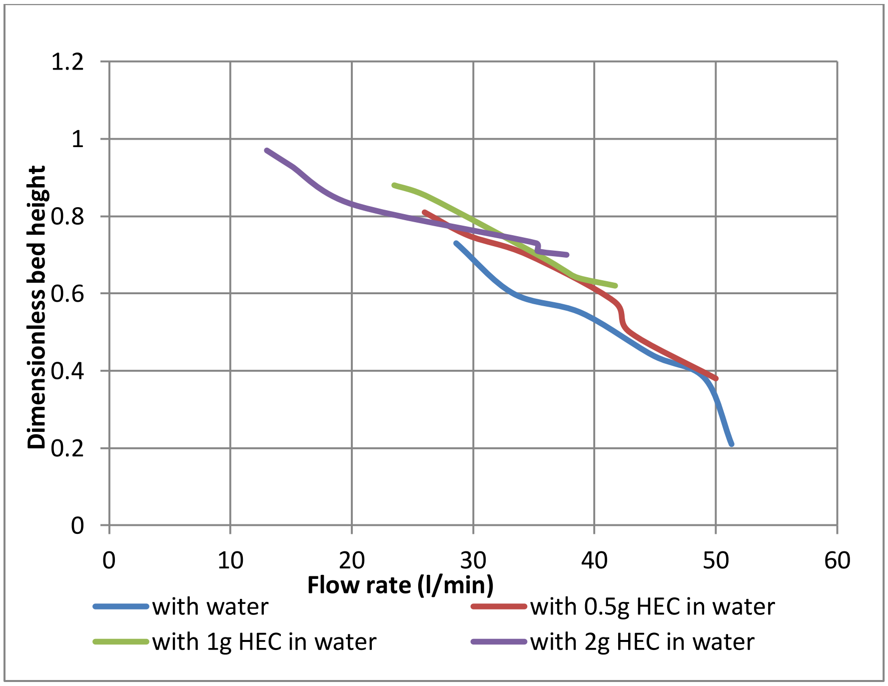

Figure 5.4: Cuttings bed height vs. flow rate in 15 cm washout

(ii) Cuttings Bed Height in 30 cm Washout

From figure 5.5, it is evident that an almost same exponential relationship exists between the cuttings bed height and the flow rates as in the case of the 15 cm washout the only difference being that the cutting height values are higher due to the higher depth to which the cuttings are deposited. Water still remains the option of choice for cleaning the cutting beds due to the fact that its low viscosity permits its flow pattern turning turbulent easily.

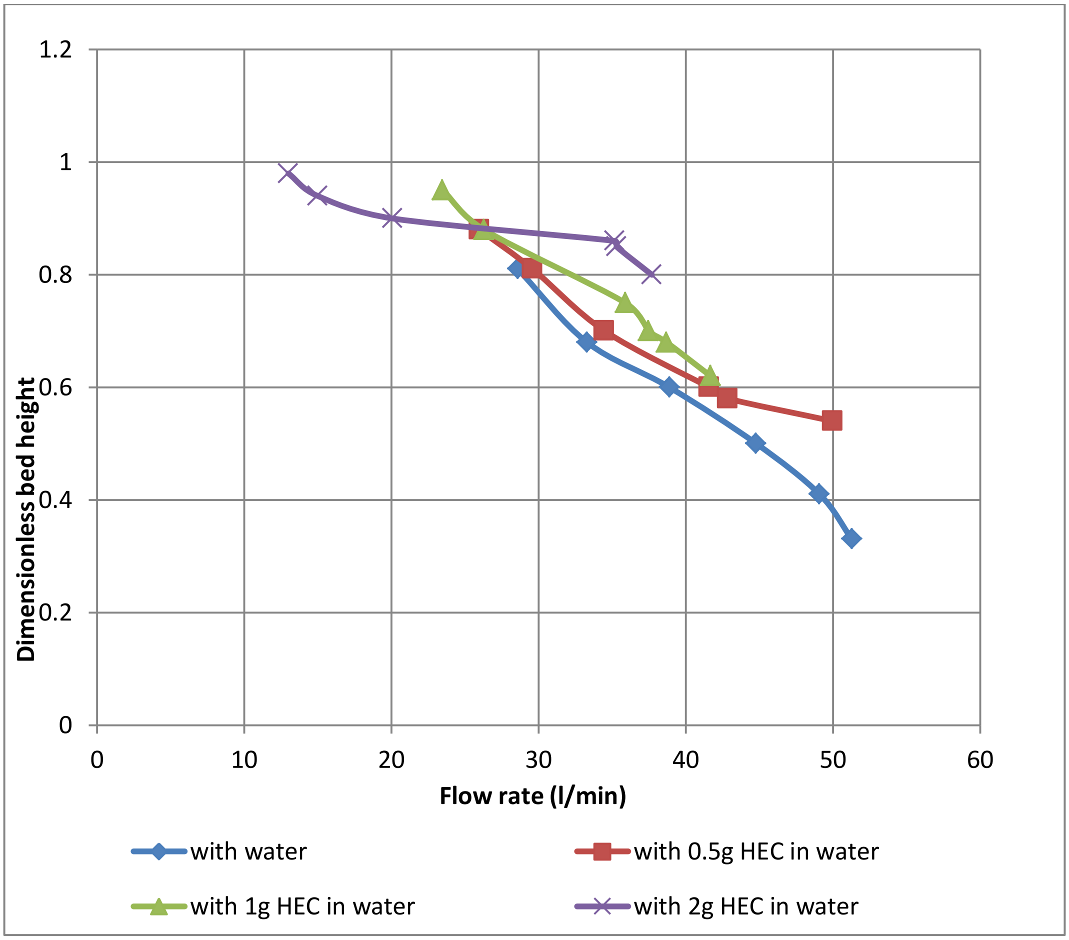

Figure 5.5: Cuttings bed height vs. flow rate in 30cm washout

(iii) Cuttings bed height in 60 cm washout

As shown in figure 5.6, the cuttings removal efficiency for the water and 0.5 gram HEC fluid were almost the same. However, the 0.5 grams HEC fluid showed better cuttings cleaning properties than the other fluids used. It is also noticed that the cuttings bed height in the 60 cm washout were the highest when compared with the 15 cm and 30 cm washout cases. The reason for this being that the larger the washout, the more cuttings accumulate in them and fluid velocity in the region reduces considerably. Besides, the fluid resistance to flow due to the high viscosity of the 2g HEC fluid caused staggering cuttings motion out of the washouts.

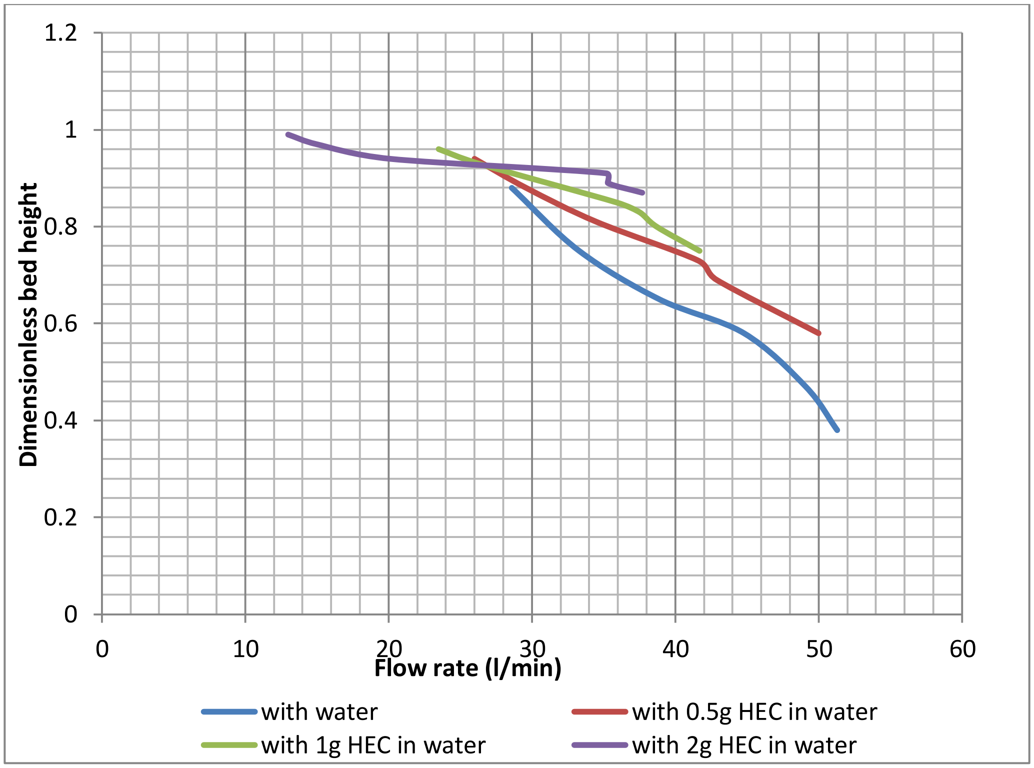

Figure 5.6: Cuttings bed height vs. flow rate in 60cm washout

5.3 Effect of Reynolds Number on bed height

For a given well, ρ and Δd cannot generally be changed. To keep a high Re number (turbulent flow), velocity v should be large and the viscosity μ should be small. Therefore, 'thin and fast' is the preferred option as it increases the chance of the mud being in turbulent flow. If turbulent flow cannot be achieved in the wellbore, then the cuttings must be removed using laminar flow. This is more difficult than with turbulent flow, and the rheology of the fluid becomes more important. The flow regime has a direct impact on the cuttings removal, and the flow can be either laminar or turbulent. The flow regime is dependent on the fluid velocity, size, and shape of the annulus, fluid density, and viscosity. The fluid flow region between laminar and turbulent is known as a transition region. In this region, the fluid has both laminar and turbulent characteristics. During drilling, rotation of drill-pipe can create a turbulent flow. When flow velocity is low or when the fluid has high viscosity, it creates a laminar flow. On contrary, the turbulent flow arises when the flow velocity is high or when the fluid has low viscosity. In addition, drill pipe or wall roughness will increase the flow turbulence. In general, it requires a higher pump pressure to transport fluid in turbulent flow than in laminar flow, the transition region between laminar and turbulent flow is controlled by viscous forces and inertial forces in the flow. In the laminar flow, the viscous forces are dominant, while in the turbulent flow the inertial forces are most important. The ratio of inertial forces to viscous forces is known as the Reynolds number. The following are the results obtained for the Reynolds numbers for the four fluids used in the test.

- **Reynolds numbers with water flow**

Reynolds number were computed from $Re = \rho V d_h/\mu$, with v the fluid velocity, ρ the fluid density, $d_h = d_2 - d_1$, the hydraulic diameter of the annulus and μ the liquid viscosity. The Reynolds numbers for the three cases of the washout is depicted in Figure 5.5. It is crystal clear from the plots in figure 5.7 that the Reynolds numbers for the fluid, in this case water was conspicuously highest in the 15 cm washout being the washout with the lowest diameter. This is due to the fact that the low flow area enhances turbulence hence high Reynolds numbers. This high Reynolds numbers leading to turbulence enhances better cuttings removal in the washouts. The plots also show the marked difference this has on cuttings bed height as the washout diameters are increased. Due to the large diameters, flow velocities of the cleaning fluid decreases substantially thereby causing the supposed turbulent flow to laminar flow. Though cuttings bed heights are reduced in each case, it is better transported in the 15 cm washout.

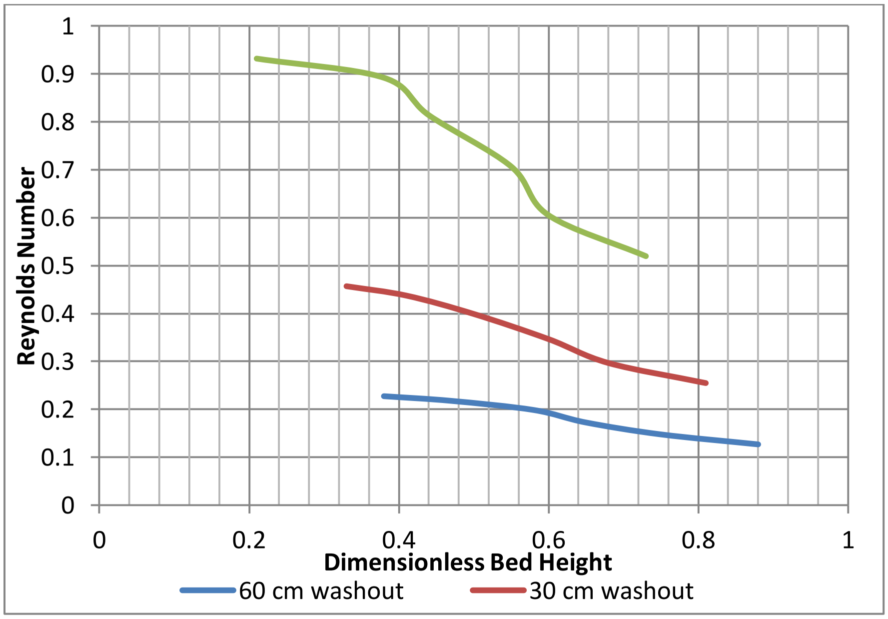

Figure 5.7: Reynolds Number vs Dimensionless bed height for water as the cleaning fluid

- **Reynolds numbers with (HEC) Slurries Flow**

The Reynolds numbers associated with the HEC fluids used in cleaning the cuttings beds in the washouts are shown in Figure 5.8 and 5.9. The Reynolds numbers show continuous decreasing values with the fluid viscosity getting higher. These values get smaller with increasing washout diameters. On the effect the Reynolds numbers have on the cuttings bed heights, we see a steady trend of decreasing Reynolds numbers yielding high stationary cuttings bed heights. In the case of Figure 5.8, the Reynolds numbers in the 15cm washout show slightly higher values than for the cases of the 30 cm and 60 cm washouts.

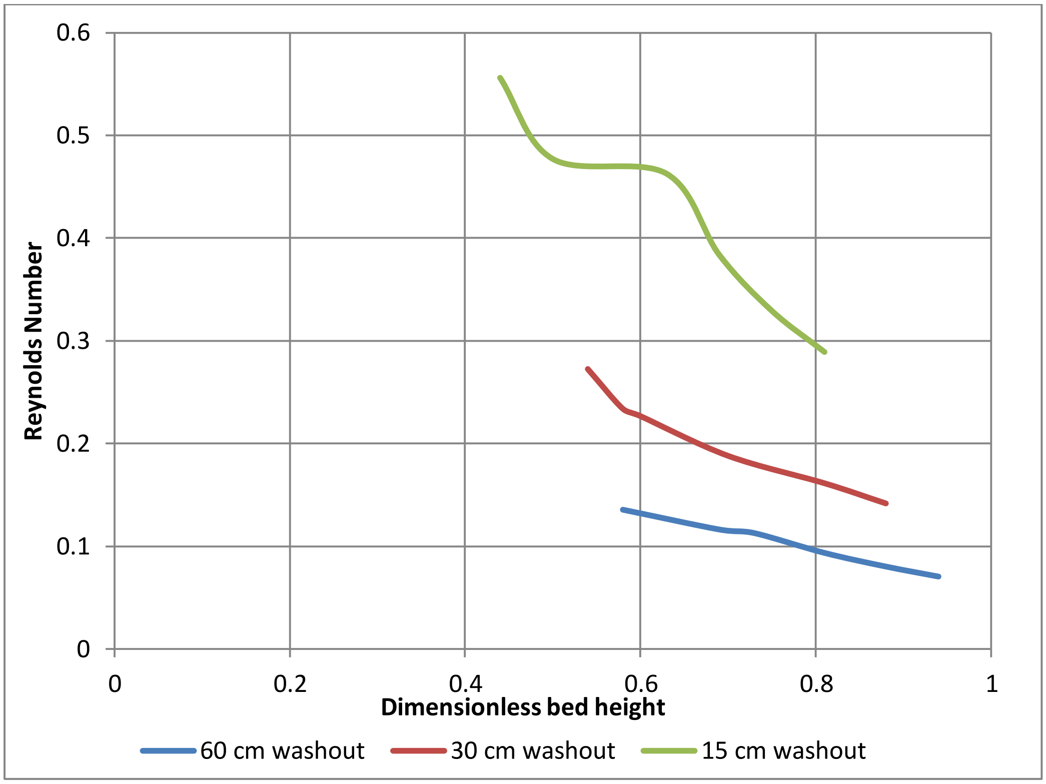

Figure 5.8: Reynolds Number vs. Dimensionless bed height for 0.5g HEC/1litre of water as the cleaning fluid

The effect on viscosity on Reynolds numbers and by extension on cuttings bed height is shown in Figure 5.9. This effect is occasioned by very low Reynolds values leading to high stationary cuttings beds showing poor cuttings removal in the washouts. The effect is more pronounced in the case of the 60 cm washout. The values are so low to the extent that little or no cuttings are transported out of the washouts. This can be explained by the fact that the fluid resistance to flow is so great such that so much energy is lost in moving the fluid over the cuttings beds. This reduces the intended rate of flow. On meeting an area with large cross section, its velocity is further reduced to an extent that its ability to remove accumulated cuttings is either reduced or non-existent.

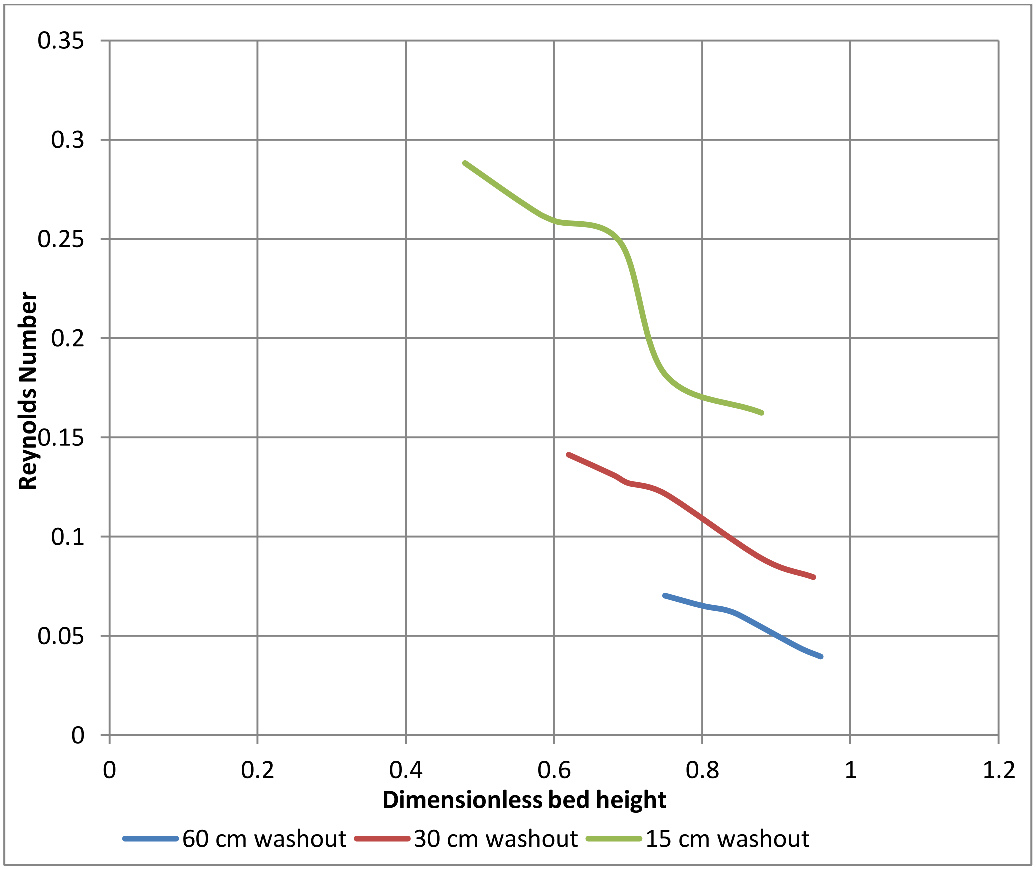

Figure 5.9: Reynolds Number vs Dimensionless bed height for 1g HEC/1litre of water as the cleaning fluid

5.4 Conclusion of the Experiment

Looking at the three cases of cuttings bed cleaning in three washout diameters of 15 cm, 30 cm and 60 cm, it is seen that the cuttings bed height in each case (water: 0.5 gram, HEC: 1 gram) increases as the diameter of the washout increased. This is evident as the cuttings height in figure 5.6 in the case of 0.5 grams HEC is higher compared with 0.5 grams HEC cases of figure 5.4 and 5.5. This can be explained in two ways namely: First, the larger the washout, the lower the fluid velocity in them and secondly, as fluid velocity reduces, cuttings accumulate more in them. Of all the fluids used in cleaning the cutting beds, water remains the option of choice. This can be attributed to the fact that the water due to its low viscosity has the potential of getting turbulent and hence enhancing cuttings removal. On the other hand, the 2 gram HEC fluid was just too viscous to remove the cuttings from the washouts.

In summary, the drilling mud flow rate is a major factor controlling the formation of cuttings bed height. As shown in figures 5.4 to 5.6, higher flow rates results in lower cuttings bed height. Again, high Reynolds numbers leads to better cuttings removal in the washouts.

6. Comparison of Experimental Results with Model Predictions

After conducting the runs for the study, the model results were verified that it yields acceptable values by comparing it with the data obtained during the experimental tests.

The details of the experimental work have been described extensively in the chapter four. Fluids used in the experiments consisted of water and solutions of Hydroxyethyl cellulose. A total of 72 tests were run on a 6-m long loop. Two types of test results were obtained:

- A visually determined cuttings bed height
- A calculated Reynolds number for the different fluids used for the test with respect to the cuttings bed heights.

The physical model presented the following hypotheses as related to washout:

- There is a bed of cuttings, lying beneath a suspension region.
- We assume that the cuttings bed is of uniform cuttings concentration.
- Fluid flow in the suspension region will apply a shear force on the top of the cuttings bed.
- These forces will be countered by friction between the cuttings bed and the hole wall. If the friction force is less than a constant multiplied by the normal force, then the cuttings bed will be stationary; if the friction force is greater than this constant multiplied by the normal force, then the cuttings bed will slide: either uphole (due to fluid shear) or downhole (a process known as “avalanching”).

The mathematical model developed in this work was based on the statistical exponential regression. The process involved deciding whether the numerical results quantifying hypothesized relationships between variables obtained from regression analysis are in fact acceptable as descriptions of the data. The validation process involves analysing the goodness of fit of the regression, analysing whether the regression residuals are random, and checking whether the models predictive performance deteriorates substantially when applied to data that were not used in model estimation.

The data points loosely define a power law relationship between flow rate and the cuttings bed height. Regression analyses show that for all cuttings sizes mud velocities, the transport rate decreases exponentially with height expression: $Q = ae^{bH}$ where, Q is the mud flow rate in metres per second, H is height in meters, a and b are regressive coefficients.

The significance of coefficient a and b in the function is defined: a represents the transport rate and b implies the relative rate with which the cuttings bed height is being transported. The two coefficients in the exponential decay function and their change imply the influence of mud flow rate on the flux profile of a moving cuttings bed. Relatively more cuttings are transported at higher levels as flow rate increases and grain size decreases, implying that saltation that gets more intense with cuttings size and flow rate is the primary transport mode responsible for the flux profile of a cuttings bed.

The cuttings bed profiles are converted to straight lines by plotting the mud flow rate, Q, on a log-scale. The slope of the straight lines that represents the relative cutting bed removal rate with mud flow rate decreases with an increase in washout diameter and cuttings bed grain size, implying that relatively more of the cuttings is transported resulting in low cuttings bed heights as mud velocity increases.

6.1 Cuttings Bed Height Comparison

Figure 6.1 presents the results of the cuttings bed height obtained experimentally with the calculated results for cuttings bed height in the developed model. The calculated and measured results show good agreement. This was done using a simple scatter plot of the experimental versus calculated bed height for the proposed model within the 10% error index. It is observed that the prediction of the proposed model also show good agreement with the experimental data except for very high flow rates where turbulence was encountered.

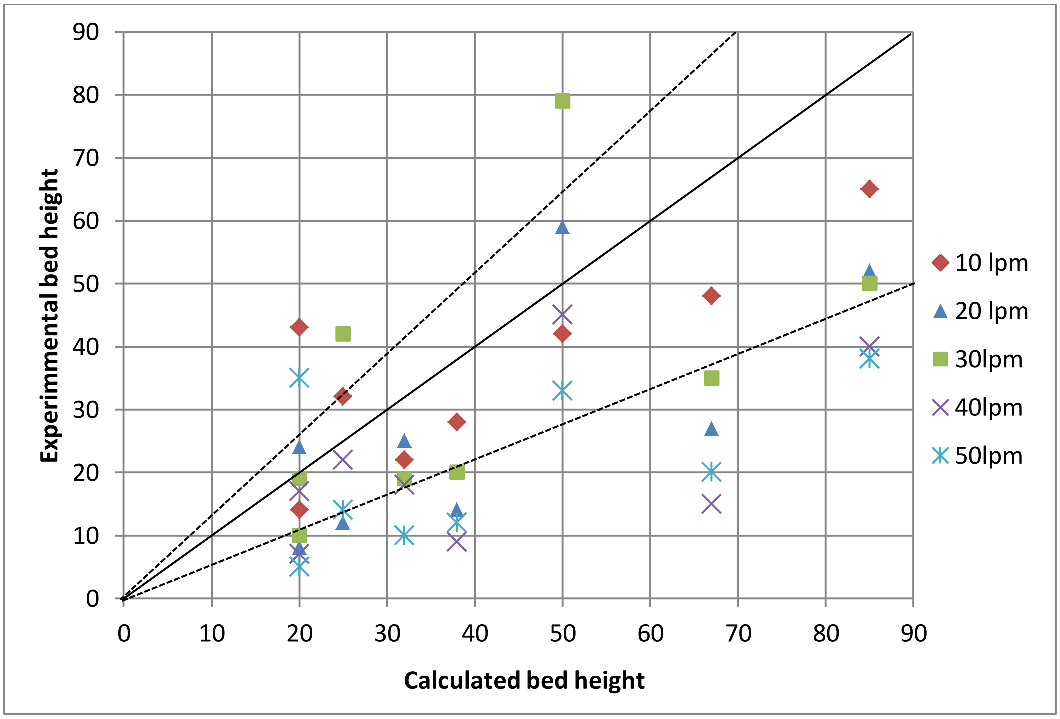

Figure 6.1: Cuttings bed height obtained experimentally vs. calculated bed height results

7.0 Discussion and Evaluation

7.1 Quality of Model

The physical model used in this work was so valuable in that it gave us a good background for a better understanding of how and why pipes get stuck in wells with washouts. The mathematical model presented showed a simplified way of relating the bed heights with the flow rates. The model however never accounted for effects of the time of flow, the wellbore inclination, pipe rotation and other parameters such as the slip velocity of cuttings, the forces acting on the cuttings bed and the settling velocity of the cuttings in the washouts. The model's assumption of the washout being smooth and cylindrical with a particular diameter could be misleading because in a typical wellbore washout condition, the washouts shows an irregular shape which can't be approximated to a cylindrical channel with uniform diameter throughout.

7.2 Quality of Test Data

The test data used in this work was of high quality especially the test conducted with water and thin mud. The thicker muds required high pump rates to initiate cuttings removal in the washouts. This would cause energy losses through friction thereby further reducing the velocity of the fluid in the washouts and by extension the flow rate. This could make the data recorded for the flow rate erroneous thus decreasing the quality of the test data.

7.3 Plans to Improve Both

My plans to improve both the quality of the test models and test data include: Making the mathematical model much more comprehensive to incorporate the effects of time of flow, wellbore inclination and other parameters such as the slip velocity of cuttings, the forces acting on the cuttings bed and the settling velocity of the cuttings in the washouts.

Also in future work, the following would be looked into:

- Investigation of entrance effects of drilling fluid into the washout section.
- Find out the critical velocity of lifting and rolling of cuttings in the washouts and then create a model for determining this velocity.
- Conduct tests with variable well inclinations.
- Conduct tests with other fluids such as CMC, PAC etc. to compare their cleaning efficiency.

- It is known that pipe rotation influences cuttings bed erosion significantly. Therefore, the model presented here needs to be further developed by including the effect of pipe rotation.
- By running test with different size of the cuttings in the washout development.

8.0 Conclusion

Stationary cuttings bed height in wellbore washouts has been studied through a simple flow loop. A comparison between the experimental and numerical results shows that the model can be used to predict cuttings bed height in the field as a function of drilling fluid flow rate and drilling fluid rheological characteristics (*n*, *K*).

The experimental results for the erosion of solid particles, the following conclusion were made:

➢ **Fluid Rheology Effect:**

Three different fluid rheologies used in a washout indicate that:

- The drilling fluid flow rate is one of the most important factors controlling the formation of a stationary cuttings bed. Increasing drilling fluid flow rates, on the other hand, decreases the cuttings bed height. For a given mud flow rate, lower cuttings bed height in the washouts is achieved as the n/K ratio increases. This means that cuttings removal is enhanced by reducing the viscosity of the fluid.
- The viscosity of the flowing fluid, besides the flow rate, plays also an important role for the erosion of a solid bed. A thicker mud will remove the cuttings at lower flow rates than that of a thin mud or water.

➢ **Bed Erosion Mechanism:**

There are two different erosion mechanisms for flow of low viscosity and more viscous fluids above a solids bed.

- For the low viscosity fluid (water), erosion starts from the front of the bed where flow is turbulent, even though it is more turbulent on the top of the bed. The erosion from the front of the bed is caused by the impact of the liquid and the resulting pressure drop (dp/dx) which acts on the projected area normal to flow.
- For the more viscous fluids (HEC) erosion starts from the top of the bed, where flow is almost turbulent, while on the front of the bed, flow is laminar for both HEC fluids. The erosion from the top of the bed is caused by the shearing action of the liquid moving above with as shear stress τ_w acting on the exposed surface area for shearing, with the impact playing a very minor role, because the exposed area of the particles is very small. Observations show that for water flow, it is impact of erosion that prevails to shearing, while for the higher viscosity HEC slurries, shearing erosion prevails.

➢ **Flow Pattern:**

Cuttings removal in the washouts was easier with turbulent flow than with laminar flow

- A high velocity with a less viscous fluid, resulting in high turbulence is effective in cutting transport in washouts while the highly viscous fluid under a turbulent flow regime easily prevents a cuttings bed from sliding downward, it can lead to pack-off or cause the drill string to become stuck in the hole during tripping.

- **Pipe and Washout Diameter**
  - If the diameter of the pipe is increased, the flow rate will decrease. Also, if the length of the pipe is increased, the flow rate will decrease due to friction.

- **Cuttings Bed Thickness**
  - Cuttings bed thickness decreases with increase in flow rate and fluid density;
  - Cuttings bed thickness decrease with decrease in fluid viscosity

Nomenclature

A = Area
A_{bit} = Area of bit
BHC = Borehole Camera
Cc = Cutting Concentration
C_D = Drag coefficient
C_L = Lift coefficient
D_{hyd} = Hydraulic diameter
D_i = Internal diameter
D_o = Outer diameter
d_p = particle density
f = Friction factor
F_B = Buoyancy force
F_D = Drag force
F_G = Gravitational force
F_L = Lift force
g = Acceleration due to gravity
H = Height of cuttings bed
HEC = Hydroxyethyl cellulose
k = Consistency Index
l/min = Litres per minute
LWD = Logging while Drilling
n = Flow behaviour index, dimensionless
N_{re} = Reynolds Number
Q = Flow rate
$Re_{(particle)}$ = Particle Reynolds number
ROP = Rate of penetration
R_t = Transport Ratio
v = Velocity
v_{lift} = Lifting velocity
v_{roll} = Rolling velocity
v^* = Shear velocity

Greek and Latin Symbols

μ = Viscosity
μ_a = Apparent viscosity
γ = Shear rate
α = Inclination angle
ρ = Density
ρ_c = Cuttings density
ρ_l = Liquid density
ρ_s = Solid density
τ = Shear stress
τ_b = Bed shear stress
Φ = Angle of repose

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APPENDIX

A: This appendix shows the values of the Reynolds numbers calculated for the flow when using water and aqueous HEC to clean the cutting beds in the washouts.

Table 5.1: Values of Reynolds number for water used as the cleaning fluid

Case I: Water: Fluid density = 1000kg/m^3, Viscosity of fluid = 1cp							
Q (l/min)	**Q (m^3/s)**	**v(m/s) in 60cm washout**	**v(m/s) in 30cm washout**	**v(m/s) in 15cm washout**	**N_{Re} in 60 cm washout**	**N_{Re} in 30 cm washout**	**N_{Re} in 15 cm washout**
28.6	0.000476762	0.002325668	0.004674137	0.0095352	0.12674892	0.25474	0.5196706
33.3	0.000555111	0.002707859	0.005442265	0.0111022	0.14757829	0.296603	0.605071
38.9	0.000648463	0.003163234	0.00635748	0.0129693	0.17239626	0.346483	0.7068247
44.8	0.000746816	0.003643005	0.007321725	0.0149363	0.19854377	0.399034	0.8140294
49.1	0.000818497	0.003992668	0.00802448	0.0163699	0.21760042	0.437334	0.8921617
51.3	0.000855171	0.004171566	0.008384029	0.0171034	0.22735034	0.45693	0.9321364

Table 5.2: Values of Reynolds number for 0.5g HEC/ 1 litre water used as the cleaning fluid

Case II: 0.5g HEC in 1 litre of water: Fluid density = 1530kg/m^3, Viscosity of fluid = 2.5cp							
Q (l/min)	**Q (m^3/s)**	**v(m/s) in 60cm washout**	**v(m/s) in 30cm washout**	**v(m/s) in 15cm washout**	**N_{Re} in 60 cm washout**	**N_{Re} in 30 cm washout**	**N_{Re} in 15 cm washout**
26	0.00043342	0.002114244	0.004249216	0.0086684	0.070518491	0.14172834	0.289125814
29.6	0.000493432	0.002406985	0.004837569	0.00986864	0.08028259	0.161352264	0.329158619
34.5	0.000575115	0.002805439	0.005638382	0.0115023	0.093572613	0.188062605	0.383647714
41.6	0.000693472	0.00338279	0.006798745	0.01386944	0.112829586	0.226765344	0.462601302
42.9	0.000715143	0.003488502	0.007011206	0.01430286	0.11635551	0.233851761	0.477057592
50	0.0008335	0.004065854	0.008171569	0.01667	0.135612483	0.2725545	0.55601118

Table 5.3: Values of Reynolds number for 1g HEC in 1 litre water used as the cleaning fluid

Case III: 1g HEC in 1 litre of water: Fluid density = 1750kg/m³, Viscosity of fluid = 4.6cp							
Q (l/min)	**Q (m³/s)**	**v(m/s) in 60cm washout**	**v(m/s) in 30cm washout**	**v(m/s) in 15cm washout**	**N_{Re} in 60 cm washout**	**N_{Re} in 30 cm washout**	**N_{Re} in 15 cm washout**
23.5	0.000391745	0.001910951	0.003840637	0.0078349	0.039621081	0.079630604	0.162446432
26.3	0.000438421	0.002138639	0.004298245	0.00876842	0.044341891	0.089118506	0.181801752
35.9	0.000598453	0.002919283	0.005867186	0.01196906	0.060527524	0.121648455	0.248162847
37.5	0.000625125	0.00304939	0.006128676	0.0125025	0.063225129	0.127070113	0.25922303
38.7	0.000645129	0.003146971	0.006324794	0.01290258	0.065248333	0.131136356	0.267518167
41.7	0.000695139	0.003390922	0.006815088	0.01390278	0.070306344	0.141301965	0.288256009

Table 5.4: Values of Reynolds number for 2g HEC in 1 litre water used as the cleaning fluid

Case III: 2g HEC in 1 litre of water: Fluid density = 2680kg/m³, Viscosity of fluid = 5cp							
Q (l/min)	**Q (m³/s)**	**v(m/s) in 60cm washout**	**v(m/s) in 30cm washout**	**v(m/s) in 15cm washout**	**N_{Re} in 60 cm washout**	**N_{Re} in 30 cm washout**	**N_{Re} in 15 cm washout**
13	0.00021671	0.001057122	0.002124608	0.0043342	0.030880646	0.062064044	0.12661065
15	0.00025005	0.001219756	0.002451471	0.005001	0.035631515	0.071612359	0.146089212
20.1	0.000335067	0.001634473	0.003284971	0.00670134	0.04774623	0.095960561	0.195759544
35.2	0.000586784	0.002862361	0.005752784	0.01173568	0.083615289	0.168050335	0.342822684
35.3	0.000588451	0.002870493	0.005769127	0.01176902	0.083852832	0.168527751	0.343796612
37.7	0.000628459	0.003065654	0.006161363	0.01256918	0.089553875	0.179985729	0.367170886

B: The pictures of the experimental setup depicting a washout section and normal section of a drilled hole.

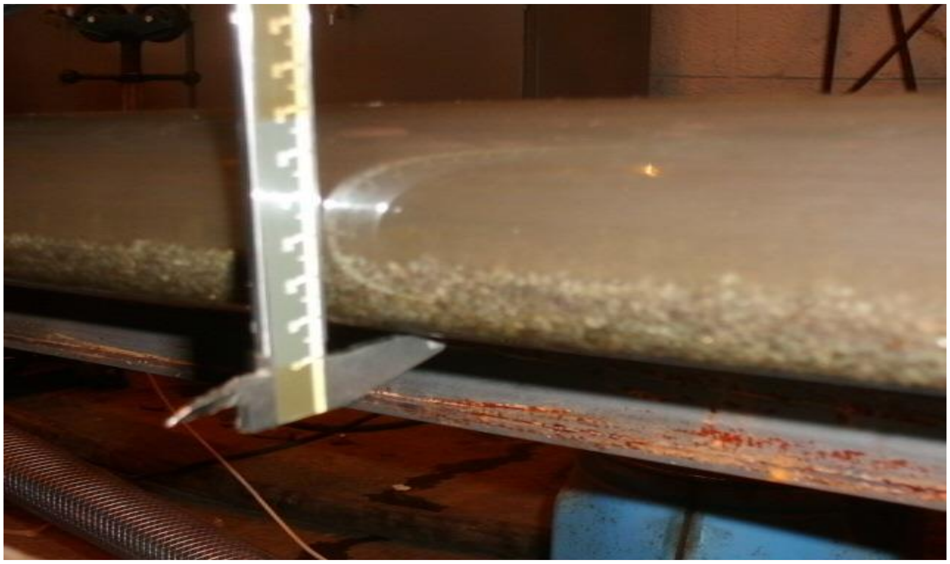

Figure B1: A washout section with 6000 ml of cuttings

Figure B2: Mixing of 0.5g of HEC.

Figure B3: cuttings in 30cm washout section

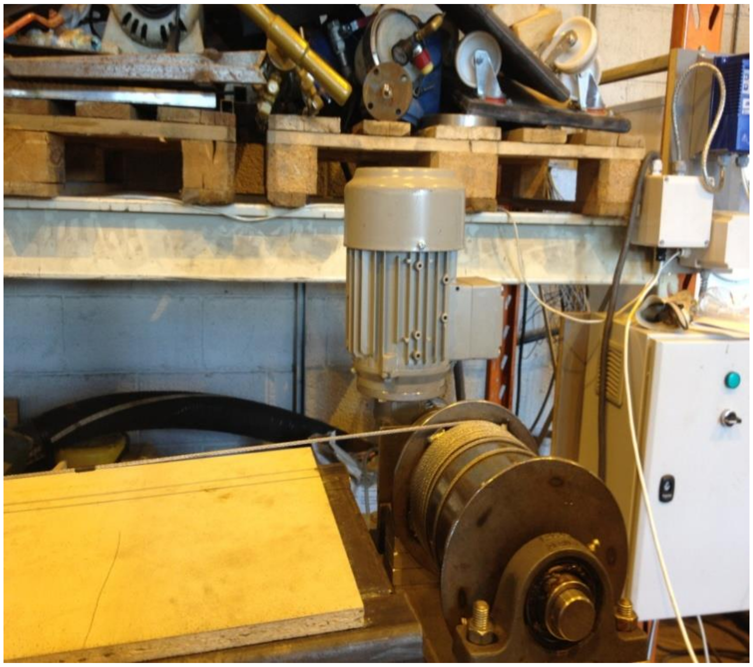

Figure B4; The pulley system

Figure B5: The flow loop setup

Figure B6: The mixer

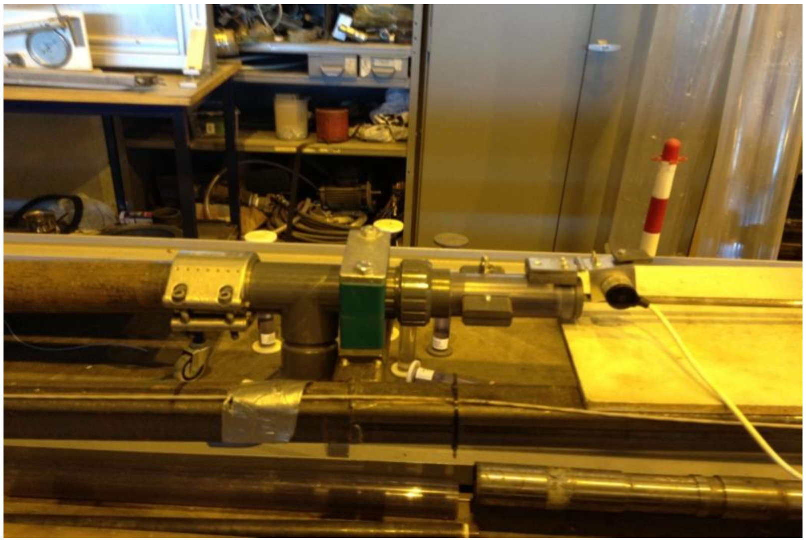

Figure B7: the winch with tachometer

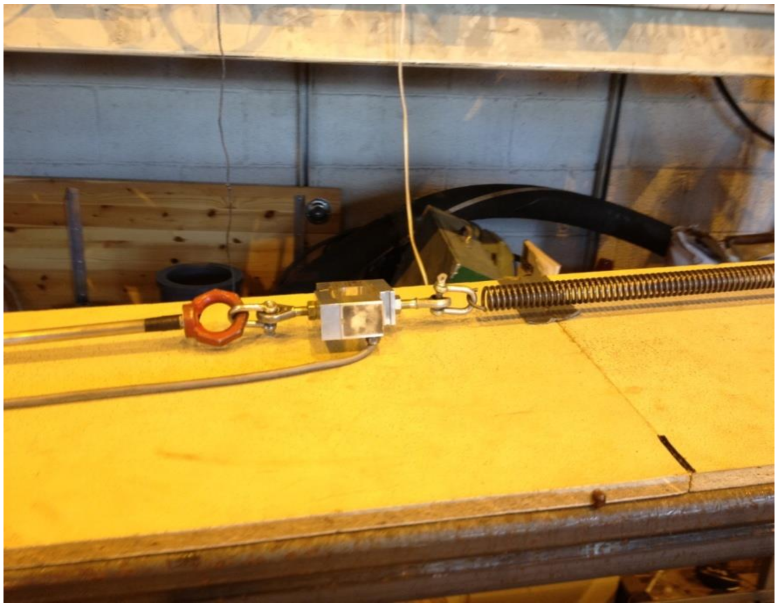

Figure B8: Spring couple with load cell

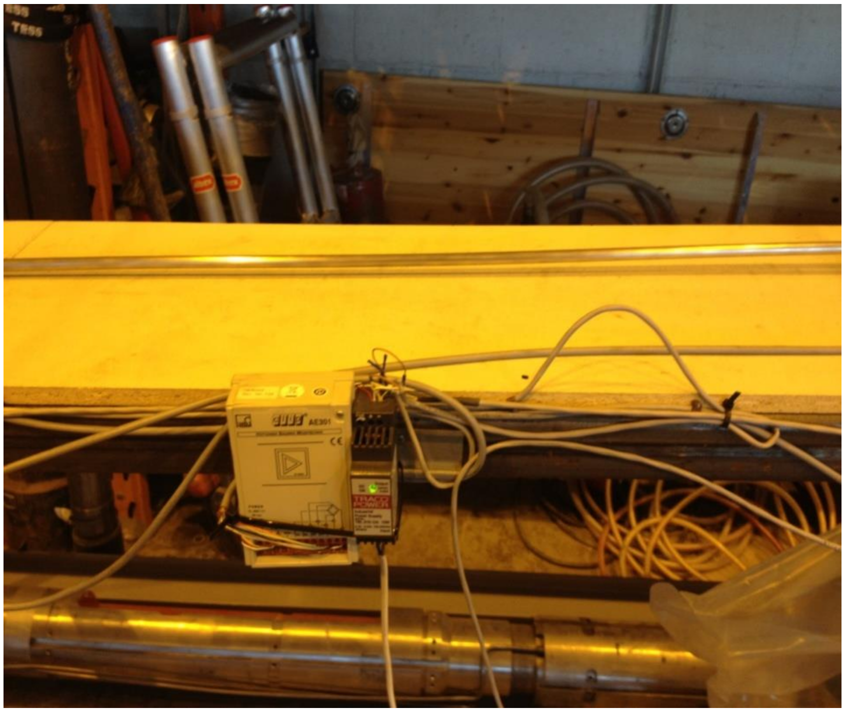

Figure B9: Tachometer