DEVELOPMENT OF A COMPUTER PROGRAM FOR SOLIDS CONTROL

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DEVELOPMENT OF A COMPUTER PROGRAM FOR SOLIDS CONTROL

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ABSTRACT

Computer software is used extensively to increase productivity and reduce man's hours of labour. This work presents the development of a solids control software (SOLCON) which is designed for real time mud system management and quick performance of routine rig computations: determination of total solids and low gravity solids content; mud property and density control requiring optimal ejection rate into the mixing pit; volume of mud and amount of barite, bentonite and additives to be added during the upgrading process of the mud. This software has the ability to evaluate the need for dilution depending on the maximum allowable drilled solids, viscosity and recommended total solids in the drilling fluid.

Finally, this software provides the atmosphere to control drilled solids as quickly as possible with all the necessary parameters.

DEDICATION

To my loving siblings

Isaac, Peter, Paul, Patience and Evelyn (Adjimah)

For their ever ready financial assistance, encouragement and words of wisdom which guided me through the years

To my mother and family

For being the best I could ask for.

ACKNOWLEDGEMENTS

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To my mother and siblings for all the emotional support you gave me. Finally to my course mates and all who meets me on the way and ask “how is your work going” may the good Lord bless all their efforts.

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CHAPTER ONE

FORMULATION OF THE PROBLEM

1.1 Introduction

Drilling fluid was introduced into the rotary drilling technology as means of transporting the drilled solids to the surface. Other function of the drilling fluids are controlling subsurface pressure, lubricating the drill string, cleaning the bottom of the hole, aiding in formation evaluation protecting formation productivity and aiding formation stability (Moore, 1986). One major function of the rig circulation system is the removal of drilled solids from the drilling mud before recirculation because of the adverse effects the drilled solids have on the drilling rate. One way of reducing drilling cost is the maximization of drilled solids removal from the drilling fluid (Field, 1972).

For sometimes now the industry has battled with various unsatisfactory solutions to the problem of solids control. These included the following:

1. A piecemeal, temporary and very expensive way to reduce solids content is by discarding part of the system and rebuilding volume with added solids, water and chemical additives.
2. The use of ‘inhibitors’ such as lime and polymers to reduce the contribution of drilled solids to mud. Generally, these materials only delays the time when a mud must be discarded.
3. A benefit more apparent than real way is the use ‘thinners’. Thinners can reduce the gel strength and the yield point of the mud (Nelson, 1970).

There are direct and indirect costs associated with drilled solids. The direct cost involves dilution and discarding of the excess volume of mud. The indirect cost is connected to the increase mud weight resulting from the presence of drilled solids in the drilling fluid. This may results in pressure differential between the drilling fluid and the formation fluid and hence reduction in rate of penetration. A reduction in hole cleaning ability as result of an increase in plastic viscosity may also lead to reduction in rate of penetration and generation of finer cuttings (Wells, 1976). Low rate of penetration increases rig time and in tend increase the cost of drilling. In order to maintain a low specific gravity of solids in the drilling fluid, about one- quarter of the volume of the drilling fluid containing the drilled solids is removed.

The three basic way to control the concentration of drilled solids in drilling fluids are; removal of solids, adding solids or their equivalent and treating solids chemically. Soluble solids and clay is added to increase yield point, gel strength, plastic viscosity and decrease filtration rate with minimum weight increase. To increase the density of the mud, barite is added with minimum effect on the mud properties and solid volume.

It is necessary to control the concentration of the drilled solids in the drilling fluid before returning it in to the drill pit. The more effectively the solids are mechanically removed the less dilution and hence the lesser the chemical treatment required (Moore, 1986).

1.2 Literature Review

Since the development of the rotary drilling technology control of drilled solids is an essential aspect of the drilling process. Several textbooks (Drilling practice manual and Applied drilling engineering) and papers (Dahi, et al 2008 and Bobo, 1953) discuss broadly how equipment and solids removal efficiency are crucial in the separation process and how drilling cost can be reduced through effective control of solids. Dahi et al.,(2008) described in details how necessary it is to optimize both filtrate efficiency and the screen life hinder the recirculation of drilling fluid containing drilled solids from entering the hole. They also explained theoretically using field examples how wear arises on shakers screen cloth and how this knowledge has been used to increase solids control efficiency that results in 90% reduction screen wear. This process was achieved by the use of different screen configurations running top screen with finer cut points.

Bobo, (1953) suggested that the maintenance of weighted mud properties may be simplified by the use of centrifugal separation to control the solids content. A new type of decanting centrifuge used in separating and rejecting the low density solid was reported to have improved the separation process. It was established that the degree of separation of light and heavy solids is not limited by the centrifuge but by the particle size distribution of drilled solids in the mud. This has been proven to be practical and economical. The author opined that one great importance of low density removal is to reduce or possibly eliminate the need for chemical treatment. This is expected to reduce the total drilling cost .The author also summarized the main application of the centrifuge process while drilling: reclaiming discarded muds and reducing the lime in content of completion fluid.

Nelson, (1970) reported on operational performance, principles and the use of newly designed centrifugal device specifically for removal of solids from the mud. The separator reclaims API barite at high efficiency. The capacity is independent of mud weight and one unit is enough for maintaining convectional rotary mud system. This flexibility of controlling the concentration of drilled solids enables it to be used widely and variably. Conyers et al., (1980) discussed that drilled solids have significant and direct effects on drilling fluids. The drilling fluid is one of the determinants of drilling cost hence is obvious that there should be a relationship between solids control and cost control. Methods of calculating the mechanical efficiency of solids control equipment on site during operation were established.

The four basic methods employed in controlling solids in the drilling muds are; force settling, dilution displacement, accelerated gravity and screening. The methods used depend on whether it is water based mud or oil based mud as well as whether it is unweighted and weighted mud. Their economic evaluation was based on cost control factors and factors requiring measurement. Shantilal, (1985) conducted an investigation on particle size distribution. He concluded that the automated particle size analyzer can be used in the laboratory as well as in the field in describing particle size distribution. In order to establish the size limit of the undesirable solids in a mud system, sieve analysis was performed using particle size distribution data between 1-129 microns. The median size measured for clay drilled solids was found to be a representative of the flocculated state of clays in different environment. Fresh unweighted water based muds were shown from measurement to be a good indication of the operation of solids control equipment. The 4 inches hydrocyclone separation efficiency was calculated and the median separation size was found to be around 35 microns which an indication of the type formation drilled.

Skidmore et al., (1985) described how drilling simulator can analysed solids control system taking into consideration the design, configuration, operation of the individual devices and the entire solids control system. They also discussed the role of solids control in overall drilling efficiency and rate of penetration. Direct comparison was established between the particle size distribution at the flowline and the mud pump suction as well as the inflow and outflow of any of the specific devices. Sophisticated solids control models have been developed to allow the drilling engineer to fine tune operation on solid control device.

Field, (1972) reported an analytical approach for drilled solids classification. He classified solids by defining the volume percentages of sands and silts in the drilling mud. His method was also used to determined particle size of drilled solids. Even though not too accurate the relative weight distribution of the particle was required to allow the removal of the particles. A numerical balanced technique was used to select the equipment that can handle the solids and how efficiently this can be operated. A balance can be run on shakers screen, cyclones and centrifuge. In doing this the rate at which feed (solids) is being produced is required i.e. the concentration of solids in the mud. Leon et al., (2004) concluded that there are three ways of discarding solids from muds; solids rejected from the system while drilling, excess drilling removed from the active system to create room for dilution and dumping drilling fluid before final well completion or abandonment. Dilution here is referred to the clean mud added to the old mud to reduce the concentration of solids in an active system

1.3 Research Methodology

Some of the problems encountered when the drilling fluid contains solids during drilling are; stuck pipe, lost circulation, excessive wear on expendables, drill string vibration, poor cement job, low drilling rates, and poor cutting transport in the annulus (Petrolskills, 2011). The size of the solids and the time of separation are very essential. Large solid particles are easier to remove than the fine ones. If the solids are not effectively removed and the mud is circulated regrinding occurs and as a result the solids are now finer and create large surface area (Newpark, 2005).

The current solid control arrangement is the use of the shale shakers as the primary controller; which enables the removal of solids larger than 74 microns. The hydrocyclones (desanders and desilters) are forced gravity settlers that increase the rate of separation by exerting force on the solids. The centrifuge usually the last on the row is used to create a centrifugal force that separates fine solids of API Barite size from the mud. The challenge encountered with this process arises during the separation process. Here the mud is diluted hence there is an increase in mud volume and this necessitates the discarding of some mud. The upgrading process of mud to its former state involves the calculation of the amount of API barite, bentonite and additives required.

1.5 Objectives

This thesis work seeks to help save rig time and hence reduce the cost of drilling by building a computer program to calculate the solids content in the mud, the volume of new mud required to be added and the amount of additives, bentonite and API barite.

1. Review Solid Control Methods
2. Develop Analytical Equations for Solids Control of Drilling Fluids
3. Develop and Validate a computer program from the equations developed in (2)

1.5 Organization of Thesis

This thesis is divided in to five chapters in which this chapter is a part. Chapter 2 contains review of the methods used to control drilled solids. Chapter 3 focuses on the testing and treatment of drilling fluids and solids removal equipment for solids control of drilling fluids. Chapter 4 discusses the development of analytical equation and program for solids control, validation of the program, results and discussions. Chapter 5 presents the summary, conclusions, and recommendations of this work.

CHAPTER TWO

REVIEW OF DRILLING FLUID TECHNOLOGY

2.1 Drilling Fluids

Drilling fluids are the most complicated fluids known to man. They are composed of about 2000 chemical additives and describe a broad range of fluids, both liquids and gases, used in drilling operations. The successful completion of an oil or gas well depends on the following: drilling fluid cost (a relative small amount); choice of the right fluid; and maintenance of the right drilling fluid properties. The total cost of a well is a function of the number of rig days, but the number of rig days is a function of penetration rate and drilling fluid related problems. Hence, the selection of the best drilling fluid and its control is the concern of all drilling personnel (Osisanya, 2011).

Drilling fluids have direct and indirect functions in rotary drilling. The direct functions includes: cooling and lubricating the bottom hole assembly, cleaning the hole, removing cuttings from mud at the surface, minimizing formation damage, controlling formation pressures, maintaining hole integrity, minimizing contamination problems, minimizing torque, drag and pipe sticking and improving drilling rate. The indirect functions involves assisting in well logging operations, minimizing corrosion of the drillstring and minimizing hole problems - surge, loss circulation, stuck pipe, pollution (Neal, 1985).

The major selection criteria for drilling fluids are (Osisanya, 2011):

- Types of formations to be drilled (mud making shales or geopressure shales, rock salt)

- Range of temperature, strength, permeability and pore fluid pressure of the formation.
- Well logging (formation evaluation) planned.
- The quality of available water.
- Environmental/ecological considerations.
- Location (onshore, offshore)
- Hole instability (hole contraction or hole enlargement)
- High angle holes (including horizontal wells)
- Productivity impairment prevention

2.2 Water based fluids

This is the most widely used mud type in the industry. It contains solids and liquids with water being the continuous phase. When the discontinuous phase is oil then it is called an oil-in-water mud and if it is air, then aerated mud (Bourgoyne et al., 1986 and Neal, 1985).

2.2.1 Fresh water mud

Many wells were drilled with the available natural fresh water in the vicinity. Drilled cuttings dissolve in the water to form mud. The resulting mud does not contain any additives except for corrosion inhibitors. The hydration of the drilled shales increases the viscosity of the mixture. This enables the transportation of other drilled cuttings to the surface. The use of available fresh water is most often deployed in holes with large diameter. The clay also has the ability to form cake on the wall of the wellbore. This reduces fluid loss to permeable regions of the formations and hence prevent borehole collapse (Bourgoyne et al., 1986 and Neal, 1985).

In order to achieve optimum mud characteristics, clays, polymers, weighting materials and additives are added to the fresh water. The weighting materials include barite, galena and iron oxides. Clays ranges from sodium and calcium montmorillonite to attapulgite and bentonite. Polymers include carboxymethylcellulose (CMC) and hydroxyethylcellulose (HEC). These additives control mud properties such as pH, gel strength, viscosity and fluid loss (Neal, 1985).

2.2.2 Inhibited water-based fluids

This type of mud is usually used to reduce sloughing problems during drilling. Inhibitive mud prevents the decomposition of drilled cuttings into finer particles and dissolving into the mud. It thus prevents the hydration of the active clay components from the formation. The hydration process also retards the structural stability of the borehole and increases the danger of its collapse. This type of mud is formulated by varying the amount of calcium, magnesium and sodium ions in the mud system. Lime muds inhibit hydration due to the presence of calcium while saturated salt solutions are used to prevent the dissolution of salt formation. Thus, gyp muds, sea water muds, lime muds and saturated saltwater muds are classified as inhibitive muds (Bourgoyne et al., 1986).

Lime mud is the most common and one of the first inhibitive mud to be used in the field. The quality of the calcium treated mud depends largely on the quantity of calcium ions that dissolves in solution. The resulting calcium hydroxide has the ability to reduce the attachment of water to the clay structure. Recently, low concentration of lime muds are used in drilling high temperature wells in order not to flocculate the clay. A popular inhibitive mud for anhydrite formations is Gyp muds. The inhibitive ability of gyp is derived from the solubility of calcium which requires thinning of the viscosity by chemical additives. It works better in low alkalinity range formations. Seawater muds are usually used when drilling offshore because of their availability. Seawater salt content reduces the hydration and dispersion of clays because of the presence of sodium chloride in it, hence its alkalinity should be checked. Sea water mud are often not saturated i.e. it can dissolve more salt in the course of drilling a salt formation. Saturated salt muds have a lot of dissolved salts in solution. They are used in drilling salt domes and thick salt stringers. Cavities found in salt formation are as a result of the use of unsaturated water-based muds used in drilling.

2.2.3 Dispersed muds

In muds of this type, chemicals are added to keep the clay platelet separated. They are usually higher solids tolerant and are very good in controlling viscosity. They are mostly used in drilling high activity clays. For example, lignosulfonate mud was reported to have been successfully used in drilling in the Gulf of Mexico and Nigeria where high activity clays are found. Chemicals used to effect dispersion are called dispersants. Sometimes, lignite and other chemical additives are added to maintain the specific properties of the mud (Neal, 1985).

2.2.4 Non Dispersed muds

Mud systems without chemicals dispersants are referred to as Non Dispersed muds. These muds are most of the time affiliated with low solids concentration and very low density weights. They do not contain chemicals, but do contain bentonite which in conjunction with the polymer present flocculates the unwanted drilled solids. This type of mud can be employed in both offshore and onshore to drill 12.1/4 inch hole. They are also used at shallower portions of the well.(Neal, 1985)

2.2.5 Flocculated muds

Flocculated muds are identified by the regular end to end structural arrangement of the clay particles. This structure prevents the easy flow of the fluid and therefore tends to increase the viscosity, gel strength and yield point of the mud. High fluid loss is also associated with this type of muds. Clay particle aggregation of flocculation may arise from an increase in the pH of the mud system to values greater than10 from mud contamination. The agglomeration of fine drilled solids due to flocculation is harnessed in control of solids (Q'Max, 2011).

2.2.6 Brines

Brines are salt water and some brine fluids used in drilling operations have low densities and low viscosities. They are also used in workeover operations where there is very low solid tolerance. The water for the production of brine should undergo filtration to eliminate all form of solids that might be present. The density here is monitored by the addition of salt or fresh water. Potassium chloride, calcium chloride and sodium chloride are usually the common types of brine. These three types of salts can be combined with other types (bromide) to form winter blends. (Neal, 1985)

2.2.7 Criteria for selecting water based muds

Normal water based muds cannot be used to drill formations having temperatures of 300ºF and above unless in the presence of special additives. Water based muds have higher frac-pressure or frac-gradient comparatively to oil based muds. This will enable them to be used in formations with larger mud window. Formations with gas production prone zones can be drilled with water based muds because it has low gas solubility; thus improving detection and handling of kick. The rheology, gel strength and density of water based muds are not strongly affected by temperature and pressure and therefore can be used in most formations. In terms of logging high salt content may not allow the use of spontaneous logs (SP). This is because the concentration of salt of the mud and formation fluid may almost be equal making it difficult to create the needed electric contrast for SP readings. Environmentally, it is the friendliest since it does not cause any pollution. Since the cost of the drilling rig may not reduce, for economic drilling, the cost of drilling fluid should be as cheap as possible. Comparatively, water based muds are cheaper comparatively since the continuous phase (water) is not expensive (Bourgoyne et al., 1986, Neal, 1985 and Slide share, 2011).

2.3 Oil based fluids

Oil based muds are muds that have oil as their base fluid (continuous phase) which is usually liquid hydrocarbons. These muds may contain water i.e. water in oil muds. Oil based muds are usually used in drilling to serve some specific function like maintenance of hole stability in hydratable formations or hydrogen sulfide bearing areas. It is always crucial to maintain the salinity of the mud greater than that of the formation when drilling in such formations. Diesel is usually the oil used because of such characteristics as good viscosity, low solvency for rubber and low flammability. Other type of oils-like minerals is being investigated in order to avoid the pollution caused by diesel. For water in oil muds, an emulsifier is added to prevent the droplet of water coalescing and coming out of solution which is used at areas of high density and increase viscosity (Bourgoyne et al., 1986 and Neal, 1985).

2.3.1 Criteria for selecting oil based muds

Oil based muds are frequently used in drilling in high pressure, high activity formations found in extreme temperature (greater than 300ºF) regions. Deep, slim and deviated holes are drilled with oil muds to reduce friction or energy loss due to torque and drag. Formations containing salt, anhydrite, carnallite, potash or active shale or H_2S and CO_2 where there will be communication between the mud and the formation if water based muds are used are good candidate for oil mud drilling. They can be used to remedy the situation of differential pipe sticking caused by mud cake from water based muds during drilling. Oil based muds may not be advisable if resistivity logs must be run since the oil serve as an insulator which does not allow the flow of current for proper formation evaluation. They also minimize corrosion problems because of its excellent lubricity and tubular wear characteristics. In terms of economics, the of cost oil based muds are determined by the degree of mud contamination and waste of muds (Bourgoyne et al., 1986, Horace, 1940 Neal, 1985, Slide share, 2011).

2.4 Aerated fluids

Aerated fluids consist of air, natural gas, mist, or aerated muds. The equipment employed in this operation is of the conventional type in addition to compressors. Mist and foam is required when large amount of drilled cuttings have to be transported to the surface under reduced hydrostatic pressure. The air is injected into the mud and pumped down the drillstring, grooved up the annulus where there is an expansion and reduction of hydrostatic pressure. Additives such as detergents are added to the air system for foaming, lubricants for friction reduction, corrosion inhibitors and viscosifires. Insufficient air volume for removing cuttings from wellbore is a problem with air natural gas drilling. Higher annular velocities cause erosion and enlargement of the wellbore resulting in an inefficient lifting of cuttings. Air bits also have special ports that are used for heat dissipation by circulating air within the bit bearings (Neal, 1985).

2.4.1 Criteria for selecting aerated fluids

Aerated fluids have enough flexibility to meet varying conditions. The use of aerated fluids eliminates the damage to producing formations as a result of bit penetration. An increase in penetration rates for zones that are too wet to be drilled which is a function of the hydrostatic pressure against the rock. It can also be used in sensitive formations where fluid lost to the formations can result in severe drilling problems which are ascribed differential pressure across the sandface. Aerated fluids used in drilling have no advantage in formation evaluation because of the ineffective interpretation of the powdery samples transported to the surface. This sample also makes the environment very unfriendly (Billy et al., 1957).

2.5 Unweighted muds

Unweighted mud is any drilling fluid that weighs less or equal to 9.5 Ibm/gal. Money is spent on this type of mud to keep the weight of the slurry up. It does not contain suspended material to weigh up or down. Table 2.1 shows a comparison between the characteristics of unweighted and weighted mud.

Table 2.1: Characteristics of Unweighted Weighted Muds (Moore, 1985)

Item	**Characteristics**	
	Unweigted mud	Weighted mud
Costliest portion	Liquids, soluble and clays	Weighted material (barite)
Size of ideal solids	Mostly clays	Mostly silt
Size of solids from the bit	Clay, sand and silt	Clay, sand and silt
Specific gravity of ideal solids	Low	high
Specific gravity of drilled solids	Low	Low
Sources of needed solids	Commercial clays, drilled clays and some silt	Commercial barite, colloids and silt
Source of detrimental solids	Drilled silt (excess) and sand	Drilled silt, clay, barite and sand
Detrimental effects of drilled clays	Minor increase in Density	Major increase in plastic viscosity
Detrimental effects of Barite clays	Not applicable	Major increase in plastic viscosity
Detrimental effects of size degradation of all solids	No problem with good removal system	Major increase in plastic viscosity
Detrimental effects of drilled silt over 44 microns	Major increase in Density, Abrasion and Filter cake character.	Minor increase in plastic viscosity and source of degraded clay
Detrimental effects of drilled sand	Major increase in Filter cake character and Abrasion.	Filter cake character, source degraded clays and variable Abrasion.
Detrimental effects of Barite silt	Not applicable	Minor increase in plastic viscosity
Detrimental effects of Barite	Not applicable	Major Abrasion filter cake character and source of degrade clays

Commercial clays and soluble solids from the formation known as inert solids are added to the mud to control the density of the slurry. This includes API barite, silt limestone, sand and feldspar. The presence these solid in unweighted muds does not necessary affect the transport of drilled cuttings to the surface. The mud filter cake resulting from this type of mud is thick and permeable instead of the usual thin and impermeable cake. The methods espoused to control solids concentration under this system are dilution, screening, chemical flocculation and forced settling. Screening is usually the first one to be applied and recent technology has shown that equipment have been made possible for removal of solids with the use of extremely fine screens which will remove the drilled solids before they are grinded to API barite size. Figure 2.1 shows particle range for common drilled solids found in unweighted water based muds.(Bourgoyne et al., 1986)

Since the natural rate of settling is too low compared to the desired rate of settling, drilling equipment such as hydrocyclones and centrifuges are used to induce a greater force beyond the force of gravity acting on the drilled solids. Addition of chemical additives can also alleviate the removal of fine drilled solids from unweighted muds. These chemicals will agglomerate the clay drilled solids into lumps which will be separated easily by the forced settlers. The drilled solids concentration not removed by the chemicals can be reduced by dilution. Dilution or water-back involves the addition of water to correct the fluid to right water-solid ratio. Because of limited storage capacity of the active mud pits, dilution requires discarding some of the mud to the reserve pits. That is a portion of the additives used in previous mud treatments are also discarded. Treatment components are arranged in decreasing order of clay size removal to prevent clogging. Dilution water is introduced upstream of the cyclone to increase cyclone efficiency. Chemical treatment is made downstream of all separation equipment to avoid discarding it along with the drilled solids (Osisanya, 2011). Figure 2.2 shows a typical arrangement of the solid control equipment for an unweighted water based fluid.

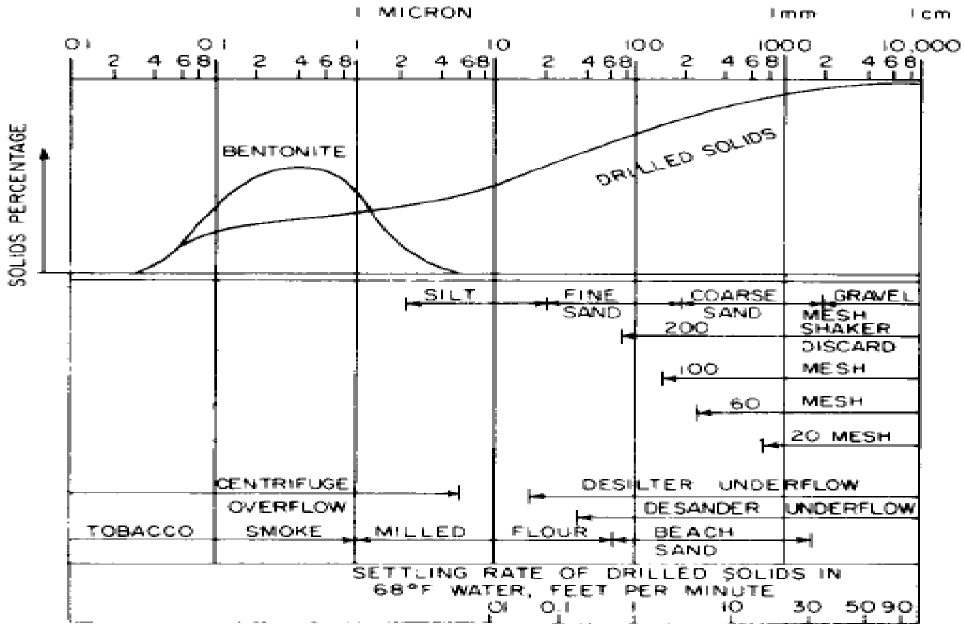

Figure 2.1: Particle size range for common drilled solids found in unweighted water based muds (Bourgoyne et al., 1986).

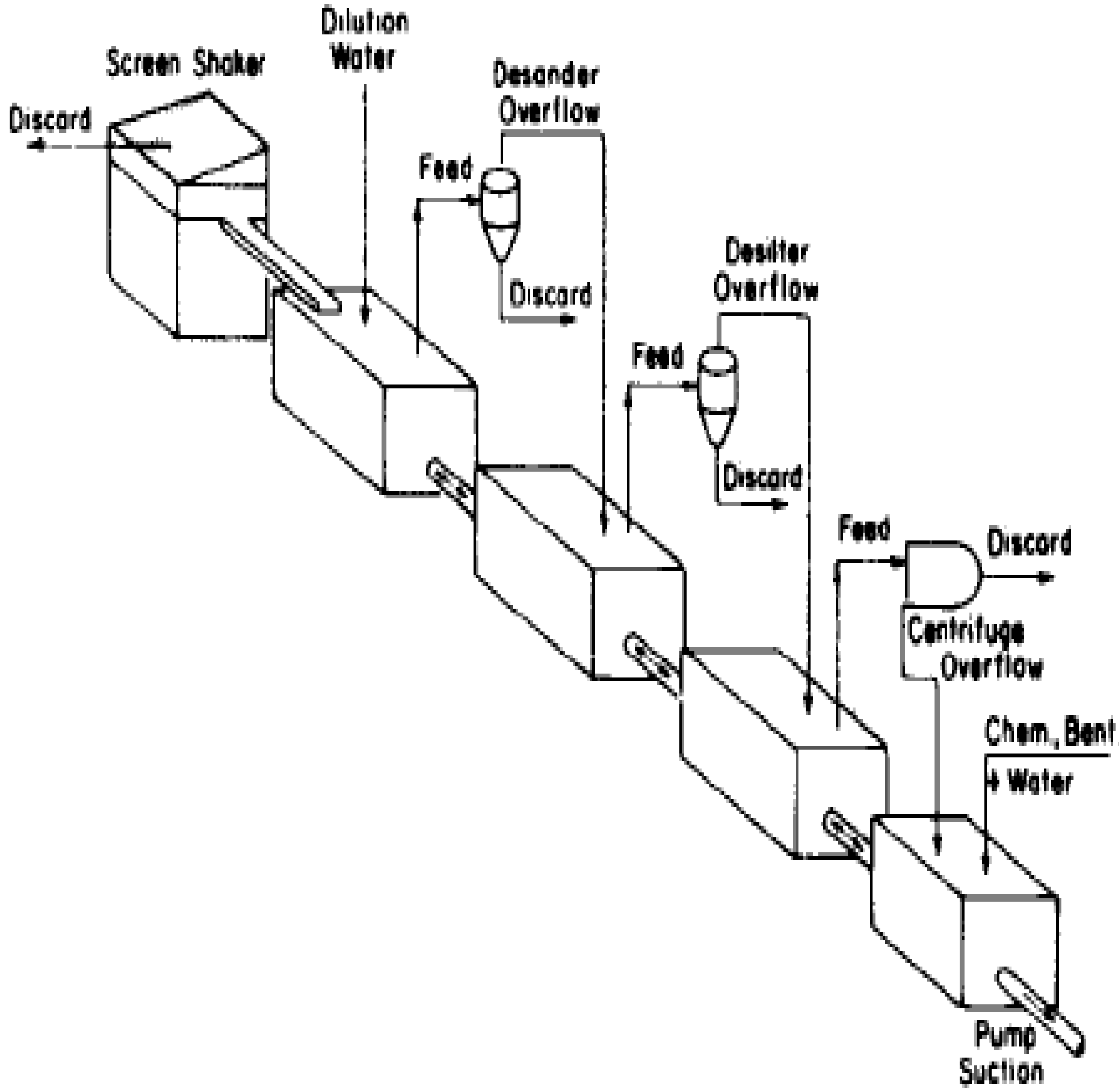

Figure 2.2: Schematic arrangement of solids control equipment of unweighted mud system. (Bourgoyne et al., 1986)

2.6 Weighted muds

Weighted muds comprises of water, active clay and inert weighting material (barite). The addition of drilled solids tends to increase the weight of the mud. Thus efforts are made to remove the low gravity undesirable drilled solids in the mud before regrinding them to API barite size. Figure 2.3 shows the particle size range for common drilled solids found in weighted water based muds. The separation process of muds weighted with barite is complicated because of the size distribution range the drilled solids and barite. Table 2.1 shows the characteristics of weighted muds. The separation process employed is the use of mud cleaner and centrifuge. Figure 2.4 shows a schematic arrangement of solids control equipment of a weighted mud system. The mud cleaner comprises of a series arrangement of hydrocyclone and shaker screen which is suited for drilling fluids of moderate mud density below 15 Ibm/gal. The screen size should not be below the 200 mesh size because of the problem of replacing barite discarded with the undesirable drilled solids. The fine drilled solids that transit the screen can be controlled by dilution and deflocculation. However this mud cleaner is not very efficient at higher mud densities because the coarse drilled solids “bypass the screen” through the mesh. (Bourgoyne et al., 1986)

The centrifuge is employed next to reduce the cost of dilution. The centrifuge separates drilled particle sizes that are within API barite size range. During this process the slurry is divided into low density mud of 9.5 Ibm/gal approximately and high density mud of 23.0 Ibm/gal approximately. The low density mud is usually discarded and the high density mud is retained in the active mud system. Also, since the volume of high density mud retained is less than what is required, new volume of mud is prepared to maintain the constant volume (Bourgoyne et al., 1986).

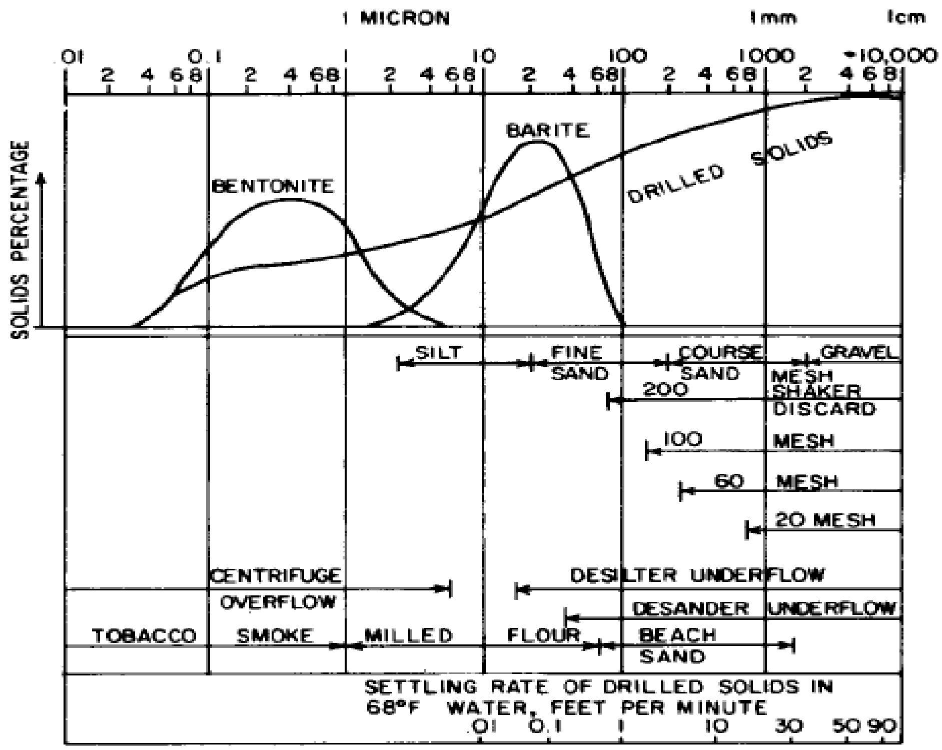

Figure 2.3: Particle size range for common drilled solids found in weighted water based muds(Bourgoyne et al., 1986).

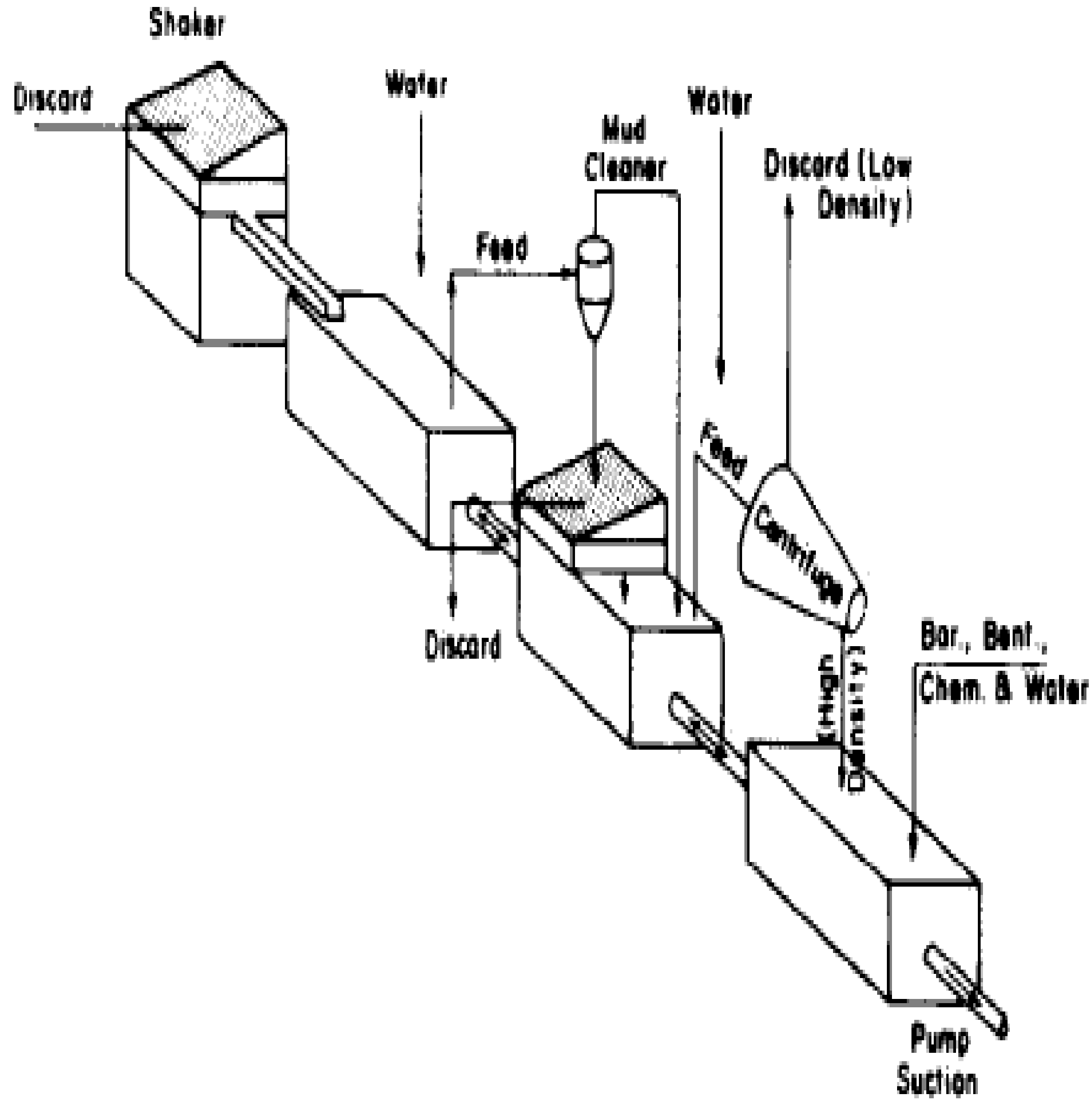

Figure 2.4: Schematic arrangement of solids control equipment of weighted mud system (Bourgoyne et al., 1986).

2.7 Importance of solid control

Solids control as part of waste management in drilling is a very important practice. For many years the drilling industry was not concerned with the amount of drilled solids in the drilling fluid. The mud circulation progresses during drilling as long as the mud could be pumped into the well. Recently, it is now a well-known fact that one of the major contaminate in drilling fluid is drilled solids, a position formerly occupied by salts and hydrates. The first measures were to treat symptoms of solid accumulation and even to accommodate fluids of higher solids concentration. The table is now turned to treating the mud by eliminating all forms of solids from it. Sometimes it is necessary to have some solids in the mud even though it may have some adverse effect in drilling (Moore, 1985). The following are some of the problems caused by the presence of drilled solids in the drilling fluid.

2.7.1 Stuck pipe

An increase in the thickness of the filter cake enlarges the contact between the drill pipe and the filter cake. For a given friction coefficient it increases the danger of pipe sticking. This problem arises when the mud density becomes high due to the presence of drilled solids (Moore 1986). Differential sticking occurs when the drill pipe becomes embedded in the thick filter cake and is enforced by the difference in hydrostatic and formation pressure.

2.7.2 Transport of cuttings

The drilled solids generally have an average specific gravity of 2.5. When the drilled solids contained in the mud weighs more than the drilling fluid, the drilled solid particles tend to slip downward through the mud. The thickness of the fluid has a direct impact on the slip velocity i.e. the fluid velocity in the annulus must exceed the downward falling rate of the drilled solids (Moore,1986 and Neal 1985). Drilled solids increases the work load on the pump which when the quantity increases, the pump cannot efficiently provide the energy for the effective removal of the cuttings.

2.7.3 Lost circulation

This is one of the major problems in rotary drilling. Lost circulation can go as far as affecting drilling cost by lost rig time, expensive remedial work and potential hole loss. Lost circulation is the loss of drilling fluid either in small quantity or in large quantity to the formation. The drilled solids contained in the mud increases the hydrostatic pressure of the mud. The high hydrostatic pressure can fracture the formation and hence serve as pathway for fluids to pass through into the formation. Due to pressure differential, fluids will flow from a region of higher pressure (hydrostatic pressure) to a region of lower pressure (formation pressure). This can also occur in porous, permeable and unconsolidated zones (Neal, 1985).

2.7.4 Torque and Drag

Torque is the amount of force required to rotate the drill string drilling i.e the main power required for drilling. Drag is the incremental force above the string weight needed to move the pipe vertically. Excessive torque and high drag cause drill string twist-off, pipe sticking and pipe parting. This may occur from high hydrostatic pressure as a result of drilled solids which may lead to formation hydration and swelling.(Neal,1985)

2.7.5 Low drilling rate

The drilling rate is affected by several properties of the drilling fluid. High viscosity muds which may be caused by drilled solids content can reduce the velocity beneath drill bit. This tends to retard equalization of the pressure around the drilled chip, thus regrinding the drilled solids before removal.(Neal, 1985) This will increase the drilling time and increase the cost of drilling.

CHAPTER THREE

SOLIDS CONTROL OF DRILLING FLUIDS

3.1 Drilling Fluid Testing

The drilling fluid testing process is one of the important aspects in rotary drilling. The resulting information obtained from testing the drilling fluid is used by everyone involved in the drilling operation. This may go a long way in saving rig time by conducting tests periodically and addressing the identified problems that may arise. In addition, the information obtained from test reports also help in planning future wells in the vicinity (Bourgoyne et al., 1986).

3.1.1 The Mud Balance

The main function of the mud balance equipment as shown in figure 3.1 is to determine the density of the drilling mud. The mud weight can be expressed in lbm/gal, lbm/ft^3 and psi/1000 ft. of depth or specific gravity (S.G). The measurement procedure involves initial filling of the cup to be weighed, setting the knife on the fulcrum and moving the sliding weight along the graduated arm until the cup and arm are balanced and finally, reading the density of the mud at the left hand edge of the sliding weight. The balance is usually calibrated with fresh water of density 8.33 lbm/gal or $62.3lbs/ft^3$ at temperature of 70°F. For proper reading, the balance is adjusted by adding or removing lead shot from the end of balance arm (Wyo-Ben, 2011). In order to ensure accurate measurement, the mud should be degassed by the fluid through the degasser (Bourgoyne et al., 1986).

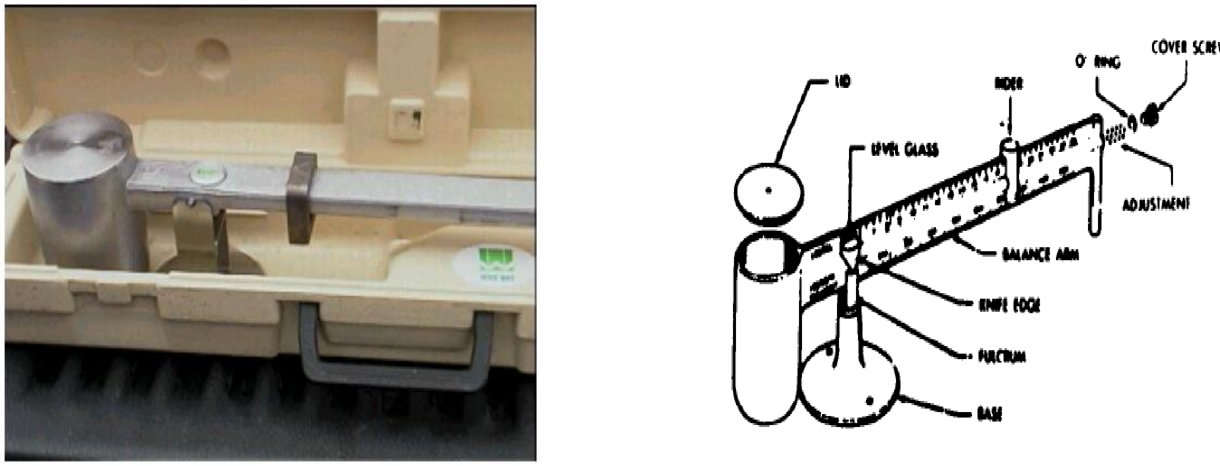

Figure 3.1: An example of a mud balance (wyo-Ben, 2011 and Bourgoyne et al., 1986).

3.1.2 The Marsh Funnel

The viscosity of the drilling mud is measured by the marsh funnel. The marsh funnel measures the actual time it takes a fluid sample to flow through a funnel. This is usually used in conjunction with the rotating viscometer to determine the actual viscous property of the drilling fluid (non -Newtonian fluid). Figure 3.2 shows the setup of marsh funnel viscometer plastic. The test consists essentially of holding funnel in upright position with index finger over the outlet. The drilling fluid is then poured through the screen in the top of the funnel until the drilling fluid reaches the marked line just beneath the screen. Finally, removing the finger from the outlet and measuring the number of seconds it takes to fill the accompanying container up to the marked 1 quart line (Section 5, 2011).

Figure 3.2: Mush funnel viscometer plastic (Yongkang, 2011)

3.1.3 The API Filter Press

This test is the most effective way of determining the filtration properties of drilling fluid and cement slurry (Yongkang, 2011). The main function is to measure the filtration rate through a standard filter paper and rate at which the thickness of the mudcake increases. This test shows the rate at which permeable formations are sealed by the deposition of a mudcake after being penetrated by the bit (Bourgoyne et al., 1986). The series Low Pressure Low Temperature (LPLT) Filter Press consists of a mud reservoir mounted in a frame, a pressure source, a filtering medium, and a graduated cylinder for receiving and measuring filtrate. The basic unit has a cell assembly constructed of rustproof anodized aluminum and chrome plated brass, and includes the required screen and gaskets. Working pressure is 100 psig and the filtering area is 7.1-in^2, as specified in the American Petroleum Institute, API Recommended Practice 13B-1 and 13B-2 (Yongkang, 2011). Figure 3.3 shows an example of an API filter press.

Figure 3.3: Filter press API (LPLT)

3.1.4 Sand Content Test

This test is conducted to determine the amount of sand content in a drilling fluid. Sieve analysis is the preferred method for this test because of the reliability of the test and simplicity of equipment. The volume of sand, including that of void spaces between grains, is usually measured and expressed as a percentage by volume of the drilling fluid. The kit (figure 3.4) consists of a special 200-mesh sieve 2½ inches in diameter, fastened inside a collar upon which a small funnel is fitted on either end. This is used with a 10 ml glass measuring tube, graduated to read from 0 to 20% the percentage sand by volume. The collar and funnel are made of polyethylene and the screen is made of brass and included is a 500ml wash bottle and carrying case (Kia, 2011).

Figure 3.4: Sand content kit (Kia, 2011)

3.1.5 The Mud Retort

This equipment (figure 3.5) provides the means of measuring and separating the volumes of oil, solids and water contained in a sample of drilling fluid. A sample of known volume is heated to vaporize the liquid components which are then condensed and collected in graduated cylinder. This cylinder is then used to determine the liquid volume by reading the water and the oil phase on the graduations. The total volume of solids (suspended and dissolved) is by noting the difference of the total sample volume versus the final volume collected. Calculations are done to determine the volume suspended solids since the dissolved solids will be retained in the retort. Low gravity solids and weight materials may also be calculated. For accurate results, a true mud density should be used for calculation. An air free sample must be used and the volume correction factor should be determined for oil content if it is present in the mud (Ofite, 2011).

Figure 3.5: An example of a mud Retort (Kia, 2011)

3.1.6 Cation Exchange

Even though the volume fraction of low gravity solids is determined, it is often necessary to determine which of these solids contains easily hydrated clay (Bourgoyne et al., 1986). The methylene blue dye test (MBT) is used to determine the cation exchange capacity solids present in a drilling mud. The reactive portions of the clay present is involved in the test and materials such as barite, carbonates and evaporates does not affect the final results since they do not adsorb methylene blue. For bentonite based mud systems, the MBT provides an indication of reactive clays which are present in drilling fluid. However, for bentonite free water based mud systems the, MBT reflects the reactivity of the drilled solids. The test cannot be used to distinguish between the types of clays but the reactivity of the drilled solids is known. It can also be used to determine the amount of bentonite present in bentonite based system (DiCorp, 2011).

3.1.7 pH Determination

The pH of a drilling fluid can be measured in two ways; the modified colorimetric using pH strips or paper and the electrometric method using a glass electrode (figure

3.6). The pH paper cannot be used for drilling fluids with high concentration of salt while the electrometric method is subject to error in drilling fluids containing high concentration of sodium ions. The pH paper strip is impregnated with dyes so that the color of the test paper is dependent of the pH medium in which the paper is placed. A standard chart is used for the color comparison. The electrode pH meter consist of a glass electrode, an electronic amplifier and a meter calibrated in pH units. Electrical connection with the mud is established through a saturated solution of potassium chloride contained in a tube surrounding the calomel cell. The electric potential generated in the glass electrode system by the hydrogen ions in the drilling fluid is amplified and is used to operate the calibrated pH meter (William, 2005).

Figure 3.6: A pH meter kit (Ofite, 2011)

3.1.8 Water Hardness

The total concentrations of magnesium and calcium in the water phase of a drilling mud determine the hardness of the mud. These contaminants can be present in the water used for the mud, cement or when anhydrite (gypsum) formations are drilled. The hardness is determined by titration with a standard (0.02N) versenate hardness titration solution (EDTA). The test is sometimes performed on whole mud as well as mud filtrate. The result from this test indicates the amount of calcium suspended in the mud and the amount of calcium in solution. In conducting the test, a sample of mud is first diluted to 50 times the original volume with distilled water so that the undissolved contaminants can go into solution. The mixture is then filtered through hardened filter paper to obtain a clean filtrate. The filtrate is then used on the API filter press to determine its hardness (Bourgoyne et al., 1986).

Figure 3.7: Water hardness test kit and water hardness testing paper (Alibaba, 2011)

3.1.9 Alkalinity

The ability of a mixture to react with an acid is called alkalinity. The amount of acid needed to reduce the pH of the filtrate to 8.3 is phenolphthalein alkalinity (end point). The mud filtrate and the phenolphthalein alkalinity is called P_m and $P_{f.}$ The P_f test includes the effect of only dissolved bases and salts whereas the P_m involves the effect of both dissolved and suspended bases and salts. The M_d alkalinity refers to the amount of acid required to reduce the PH to 4.3 i.e. the end point of the methyl orange. M_f and M_m is the methyl orange test performed on the filtrate and the mud respectively. All results are reported in cubic centimeter of 0.02N (normality = 0.02) sulfuric acid per cubic centimeter of sample. The P_f, P_m and M_d is designed to determine the hydroxyl, bicarbonate and carbonate ions concentration in the aqueous phase of the mud (Bourgoyne et al., 1986).

3.1.10 Chloride Concentration

Chloride concentration is determined by titrating with silver nitrate in solution. This results in the removal of chloride as white precipitate ($AgCl^-$) from the solution. The end point of this titration is detected using potassium chromate indicator where the Ag left in solution after removing the chloride reacts with the chromate to form an orange red precipitate (Ag_3CrO_4). Contaminants of chloride usually results in drilling salts formations or saline formation water can enter the wellbore (William, 2005).

3.1.11 Chemical Analysis

Standard chemical analysis has been developed for the determination of concentration of various ions present in the drilling fluid. Test for chloride, hydroxyl and calcium ion concentration is required to fill out API drilling report. The test is based on reaction of a known volume of mud filtrate sample with a standard solution of known volume and concentration. The end of the chemical reaction is usually indicated by the change of color whereas the concentration of the ion being tested can be determined from knowledge of the chemical reaction in progress (Bourgoyne et al., 1986).

3.1.12 Gel Strength

Gel strength is the measure of the inter-particle force and is an indication of the gel that will form when circulation is stopped. This property prevents the cuttings from settling in the hole. Gel strength is measured in Ibf/100ft^2 and this is obtained by reading the maximum dial direction when rotational viscometer is turned at a low rotor speed

(3rpm) after the mud has remained static for some time (10 seconds, 10 minutes). This result is reported as initial gel on the API mud report form. This device is also used to determine the yield point. High pump pressure is required to break the gel (William, 2005).

3.1.13 Resistivity

In order to enhance the evaluation of formation characteristics from electric logs it is necessary to determine the resistivity of the mud. The resistivity determination is the measure of flow of current through the known sample configuration. The measured resistance is converted to resistivity by the use of cell constant. This cell constant is fixed by the configuration of the sample in the cell and is determined by calibration with standard solutions of known resistivity. The resistivity is expressed in ohm-meter (William, 2005).

3.2 Treatment of Drilling Fluid

Contaminated drilling fluid is a considerable hazard to drilling operation. The appropriate process to treat fluid before recirculation is very important. The basic ways for treating tested drilling fluids are as follows (Moore, 1986):

- Removal of solids (drilled solids) from the mud.
- Addition of solids (barite, bentonite) or their equivalent to the mud.
- Treatment of solids (drilled solids) chemically.
- Dilution of mud

3.2.1 Removal of Solids

In order to return drilling fluid to the bit, undesirable drilled solids must be removed. The recirculated drilling fluid should be its optimum properties as economically as possible. If all drilled solids are effectively removed mechanically (shale shaker, centrifuge), there would be less requirements for dilution and chemical treatment. There will not be any need for separation if the fluid from the annulus is discarded after each bit rotation. This is not very economical in all cases (Moore, 1986).

3.2.2 Addition of Solids

Solids are added to the drilling fluid for specific controls. Solids such as soluble solids and commercial clays are added to increase yield point, gel strength and plastic viscosity. They are also added to reduce filtration rate with minimum weight increase. In addition, heavy commercial silt solids are added to increase the density of the slurry in order to maintain solids volume and mud properties (Moore, 1986).

3.2.3 Chemical Treatment of Solids

This is the science and art of adding specific soluble material to a drilling fluid to alter the behavior of some specific solids directly or indirectly in the fluid. The chemicals usually act on the clay particles, including hydratable shales but do not have any effect on the lager inert particles. Even though chemicals such as salt may be soluble, they do not add to the true total solids. In order to reduce the cost of chemical treatment, chemicals should be added upstream (Moore, 1986).

3.2.4 Dilution of Mud

Dilution is the process of adding water or the base fluid to the mud to reduce the concentration of drilled solids in the mud. It is very important to determine the dilution factor. Unproportional dilution can results in elevated properties, increased solids and high filtration rates which may results in excessive treatment and fluid system cost. This can also give rise to excess volume discharge and higher treatment cost (Newpark, 2005). In order to reduce the cost of dilution, dilution should be done downstream, mud volume should be kept small, old mud should be discarded before dilution and one step dilution rather than small frequent dilutions (Bourgoyne et al., 1986).

3.3 Solids Removal Equipment

Solids are deliberately added to drilling fluid to increase the density (high gravity solids) or to improve the rheological, chemical and filtration properties (low gravity solids). The fluid gets contaminated when drilled solids enter the mud. If this low gravity solids are not removed on time and allowed to accumulate, they might break into fine solids thereby occupying lager surface area. This will put pressure on surface equipment; reduce rate of penetration and increase viscosity and filtration rate. The resulting effect will eventually increase the total cost of drilling. The various mechanical separation devices separate solid particles by size. Table 3.1 shows classification and size of solids (Newpark, 2005).

Table 3.1: shows classification and size of solids (Newpark, 2005)

Classification of Solids	**Example**	**Particle Size Range**
Coarse	Small cuttings, gravel	>2000 microns
Intermediate	Coarse sand	250-2000 microns
Medium	Fine sand	74-250 microns
Fine	Coarse silt	44-74 microns
Ultra-fine	Barite, fine silt	2-44 microns
colloidal	Bentonite, clay	< 2 microns

3.3.1 Shale Shakers

Other mechanical separation devices cannot operate effectively unless the shale shaker is employed. The term shale shaker used in drilling operations cover vibrating screens, shaking screens and oscillating screens (Moore, 1986). This device (figure 3.9) has the capability in removing all drilled solids larger than 74 microns when 200 mesh screen size is employed. It is the only separator that can accommodate and handle the full flow of the drilling fluid as it comes straight from the hole. The shakers are usually equipped with the finest mesh which enables them to accommodate the anticipated flow. Approximately, 75% of the screen area should be occupied by the fluid flowing out of the hole. This will create the adequate retention time needed to separate the drilled solids from the mud. Different types of shaker have flexibility of raising the cuttings to the discharge end of the screen. This attribute helps in absorbing any surge in the mud flow by increasing the retention time of the cutting on the screen. If the angle of inclination is too high, the cuttings instead of being transported off the screen will accumulate at the back of the shaker and this eventually cause the breakage of the screen due to shear weight (Newpark, 2005).

The screen selection can be decided in advance based on factors such as hole diameter, deviation and pre knowledge of the formation to be drilled. The median cut-size particle is that size of which half pass through and half is rejected over the top. Shales formations are usually drilled at high rate of penetration and this will cause the screens to plug. Scalping shaker fitted with coarse screen will reduce cutting weight on the finer screens. The reduced weight on screens when drilling 12.25” hole should allow the installation of 150 mesh. In the 8.5” hole, 200 or 230 mesh should be installed. In order not remove the barite in weighted muds, this finest (200, 230) mesh size should be used. Finer screens have shorter life span compared to coarser screens and are very sensitive and hence overloading with cuttings and loss of liquid mud should be avoided (Newpark, 2005). Figure 3.8 shows examples of screens.

Mesh of screens comes in different shape, square or rectangular openings. Rectangular mesh screens have larger open area and tend to reduce the blinding effect experienced along sand sections. However some solids will pass through the rectangular opening which would have been successfully removed by square mesh. Table 3.2 shows mesh and aperture size of shaker screen. The life of the screen can be increased by cleaning it from the underside to avoid breaking the solids and forcing them through the mesh into the mud. The cleaned and new screens can be stored under cover in a dry place (Newpark, 2005).

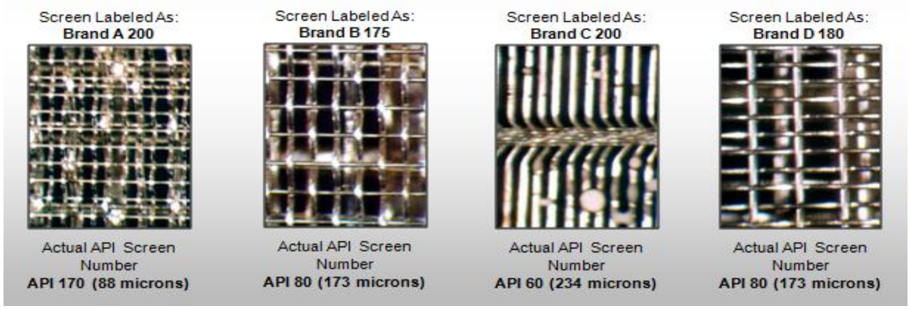

Figure 3.8: Examples of Screen Mesh (Wells, 1976)

Figure 3.9: An example of a shale shaker (NOV, 2011)

Table 3.2: Mesh and Aperture Size of Shaker Screen (Newpark, 2005)

Screen mesh	Aperture size (microns)
8 x 8	2463
12 x 12	1524
20 x 20	863
30 x 30	515
40 x 40	381
60 x 60	234
80 x 80	178
100 x 100	140
150 x 150	105
200 x 200	74

3.3.2 Degasser

This device (figure 3.10) is sometimes necessary to the solids removal process. The shaker cannot remove all the gas from a badly gas-cut mud especially with muds having yield point lower than 10 lb/100 sq ft. It is usually a common practice that mud yield point equal to or less than six does not require any degassing equipment. Centrifugal pump feeds the hydrocyclone and abrasiveness for oil field muds is not efficient when they contain gas. If the pumping (feed) head of the hydrocyclone is not constant or contains gas or air in the feed, it will not perform well (Moore, 1986).

Figure 3.10: An example of a Degasser (NOV, 2011)

3.3.3 Hydrocyclones

Solids particles will always settle in any liquid they are denser than. Hydrocyclone devices such as desanders and desilters increase the rate of drilled solids separation by increasing the exertion force on the solids particles. The fluid is pumped into the tangential cone which creates a centrifugal force. The solids particles move against the wall of the cone and fall to the bottom when they are discharged. The clean mud is discharge through the top of the cone as shown in figure 3.11. Hydrocyclones are manufactured in different diameters and the diameter of the cone dictates the average solid particle size to be removed. They are designed with specific hydrostatic head and this is a function of the mud weight. The pressure of the feed increases with increasing mud weight and the feed pressure will vary with the density of the fluid going through the hydrocyclones (Newpark 2005).

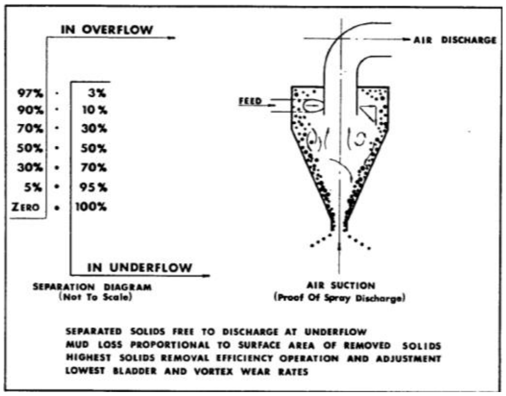

Figure 3.11: A balanced design of hydrocyclone (Moore, 1986) and an example of a hydrocyclone (Desilter) (NOV, 2011).

3.3.3.1 Desanders

This device is a cone of 10-12 inches in diameter and has a capacity of 3000-400 gal/min. It can only remove solid particles of about 74 microns. Desanders have the disadvantage of discharging barite and some additives with the mud and hence should only be used for unweighted and inexpensive muds (Newpark 2005).

3.3.3.2 Desilters

A desilter cone is 4-6 inches in diameter and has 50-80 gal/min capacity of fluid it can contain. The median cut point is about 20 microns. In addition to removing drilled solids, this device can also remove coarse barite, additives and

40-65 gal/hr fluid. Desilters cannot be used for oil or synthetic based muds and muds containing approximately >200 lb/bbl barite (Newpark 2005).

3.3.4.5 Mud Cleaners

The installation of any of the above cones with vibrating screens can extend the use of the hydrocyclones. The discharge coming from the desilter is passed over the screen in which, the fluid and most barite is recovered and the drilled solids discharge. Mud cleaners can make about 65-105 microns when is in conjunction with 150-230 mesh screen. They are usually used where the shale shaker cannot install with fine screens and also in weighted muds (Newpark 2005).

3.3.5 Centrifuge

This device like hydrocyclones creates a high centrifugal force to separate solids of API barite size from the fluid. Fluid is pumped into a rotating cylinder where the solids are forced against the wall. As the rotation continues, a bladed screw inside the cylinder transports the drilled solids to the discharge. Ultra-fine and colloidal solid particles are discharged through an overflow port. This separation process employs Stoke's Law, where an increase in centrifugal force improves finer solid particle separation. Based on this same law, different solids of the same size but different densities, the denser solid particle settle faster than the lighter one. Usually, the centrifuge cannot distinguish between barite and fine solids but will normally remove barite particles which are approximately lower than 30% of the finest drilled solids. The centrifuge cannot process the full flow of the fluid as it comes from the hole. Thus the viscosity is a function of the maximum feed rate. An increase in the speed of rotation enhances the separation process but the throughput of the cone will have to reduce (Newpark, 2005).

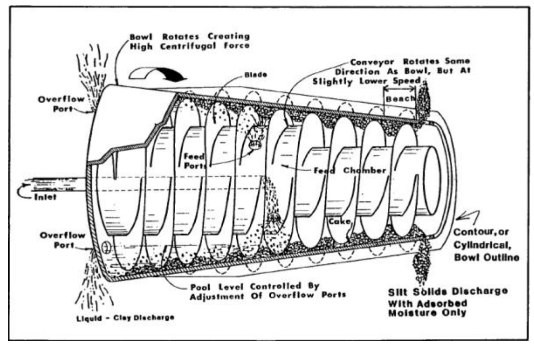

Figure 3.12: An example of centrifuge (NOV, 2011) and decanting centrifuge, sectional view (Moore, 1986)

CHAPTER FOUR

DEVELOPMENT OF A PROGRAM FOR SOLIDS CONTROL

4.1 Solids Control

This chapter elaborates on the use of a computer model (SOLCON) to simulates the performance of the shale shakers, hydrocyclones and the centrifuges in solids control of unweighted and weighted muds. There are various equations employed in controlling drilled solids. The major equations adopted in this work are from Advanced Drilling Engineering (Bourgoyne et al., 1986) and Equipment Solids Removal Efficiency for Minimum Volume of Drilling Fluid to Dilute Drilled Solids (Leon et al., 2004). Solids control equipment is arranged such that the particle size limit for equipment is the starting point for another. For instance, the hydrocyclone separates drilled solids that are smaller than 74 micron which the shale shaker of 200 mesh screen cannot remove.

4.2 Program Development

SOLCON was designed using Java 1.6 with Netbeans 6.9.1 software program. This program can be on run many different platforms. The ability to run the same program on different system is crucial to the drilling industry. It can also be used in conjunction with other programs since Java is automatically heterogeneously compatible with other softwares (MS Article Review, 2009). An incorrect or correct application of SOLCON will not interfere or cause any problem to the rest of the computing environment. Launching the SOLCON software involves clicking on the icon which introduces the main interface requesting for security verification. On this platform, any desired calculation on solids control can be selected.as shown in Fig 4.1 Data can be entered in the Data Worksheet. There are a number of data that can be entered per panel and this may change depending on what is being calculated. For instance when you want to calculate the amount of barite (mB) based on limited volume or unlimited volume under “Density Control or Basis for Dilution”, the label and text cells changes in accordance to what is selected from the “Combo Box”. The combo Box found on any of the panel when drawn down either gives one the option to select or to continue a calculation process.

Data can only be entered in the editable and the white coloured cells while the non-editable grey coloured cells are automatically calculated. As the data is being entered, there is need to ensure that the required units are checked. Before clicking the “Ok” button to compute the final result, take a final look at the worksheet and check for any bad data due to typing errors. The “Clear” button is used to erase from the editable cells while the \][]Exit” button is used to exit the interface. Most of the panels are linked to each other so computed values from one panel can be used in another when required. The software also gives you the opportunity to either input data or call it from the system. The help under file menu item as shown in Fig 4.2 will help on how to use the software and understand how it works.

4.2.1 Solids Control for Unweighted Mud

Assumptions

- The drilling operation is gauged i.e. bit diameter is equal to the diameter of the well bore.
- The volume of fluid discarded is equal to the volume of fluid added.

Total volume of drilled solids excavated (V_s), bbl/hr

Figure 4.3 and 4.4 shows the flowchart and the interface of weighted muds

$$V_S = \frac{\Pi(1-\phi)d^2}{4}\frac{\partial p}{\partial t} \qquad 4.1$$

$\frac{\partial D}{\partial T} = penetration\ rate,$ ft/hr

φ = porosity

d = diameter, in

4.2.1.1 Hydrocyclone Analysis

$$\rho = \frac{m_s + m_w}{V_s + V_w} = \frac{\rho_s V_s + \rho_w V_w}{V_s + V_w} = \rho_s f_s + \rho_w f_w \qquad 4.2$$

ρ = density of mud, lbm/gal

m_s = mass of solids excavated, lbm

m_w = mass of water in the mud, lbm

V_w = volume of water in the mud, bbl

ρ_s = density of drilled solids, lbm/gal

ρ_w = density of water, lbm/gal

f_s = volume fraction of solids

f_w = volume fraction of water

4.2.1.2 Ejection calculation

$f_s = \frac{\rho - \rho_w f_w}{\rho_s}$ From equation (2)

$$m_s = V_s * \rho_s \qquad 4.3$$

$$m_{se} = f_s * r * \rho_s \qquad 4.4$$

$$1 = f_{bf} + f_s \qquad 4.5$$

$$f_{bf} = 1 - f_s$$

$$V_{we} = f_{bf} * r \qquad 4.6$$

m_{se} = mass rate of solids ejected, lbm/hr

V_{we} = volume rate of water ejected, gal/hr

f_{bf}= volume fraction of base fluid

r = rate of ejection of slurry (volume/time)

4.2.1.3 Dilution Based on Volume Drilled

Drilling fluid built (V_{mb})

$$V_{mb} = \frac{V_{bf}}{f_{bf}} \qquad 4.7$$

V_{bf} =volume of base fluid added or volume fluid discarded, bbl

Total dilution (D_t)

$$D_t = \frac{V_s}{f_s}$$

Dilution factor (D_F)

$$D_F = \frac{V_{mb}}{D_t} \quad 4.9$$

Drilled solids system performance

$$SP = (1 - D_F) * 100 \quad 4.10$$

SP = system performance

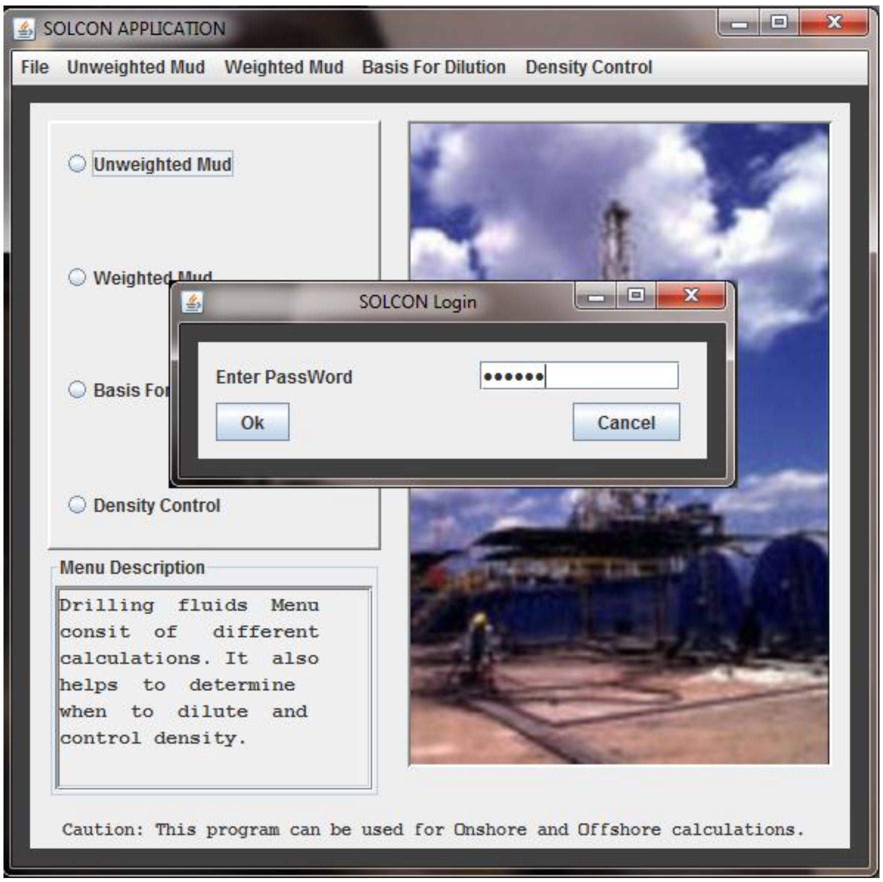

Figure 4.1: The Launching interface showing calculation types

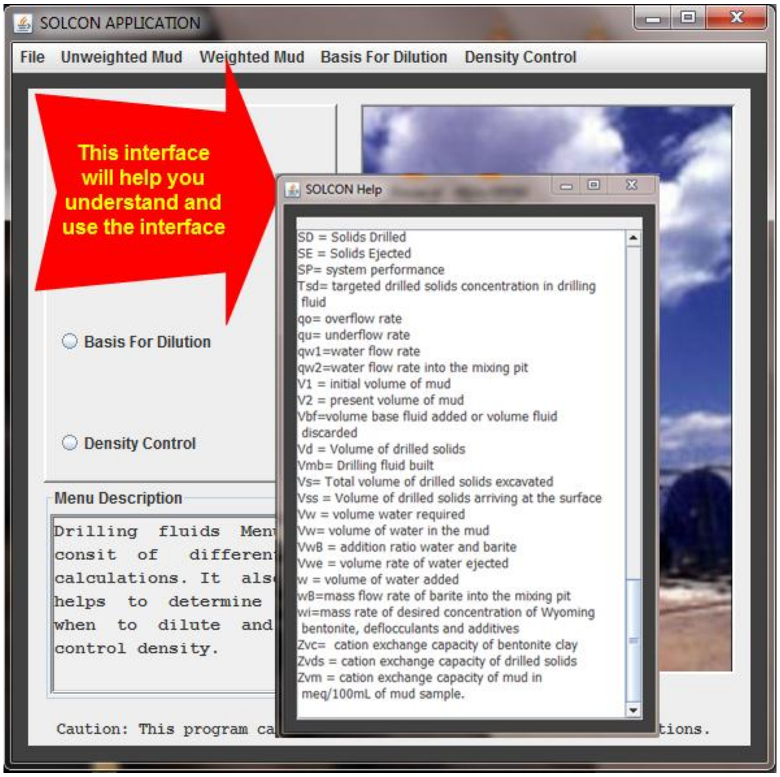

Figure 4.2: An interface showing the help

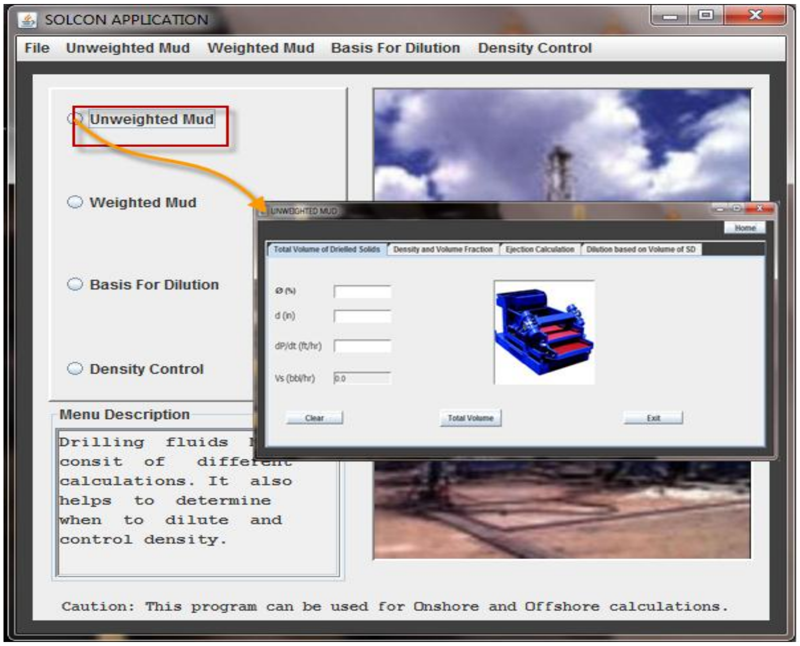

Figure 4.3: An interface showing unweighted mud calculation

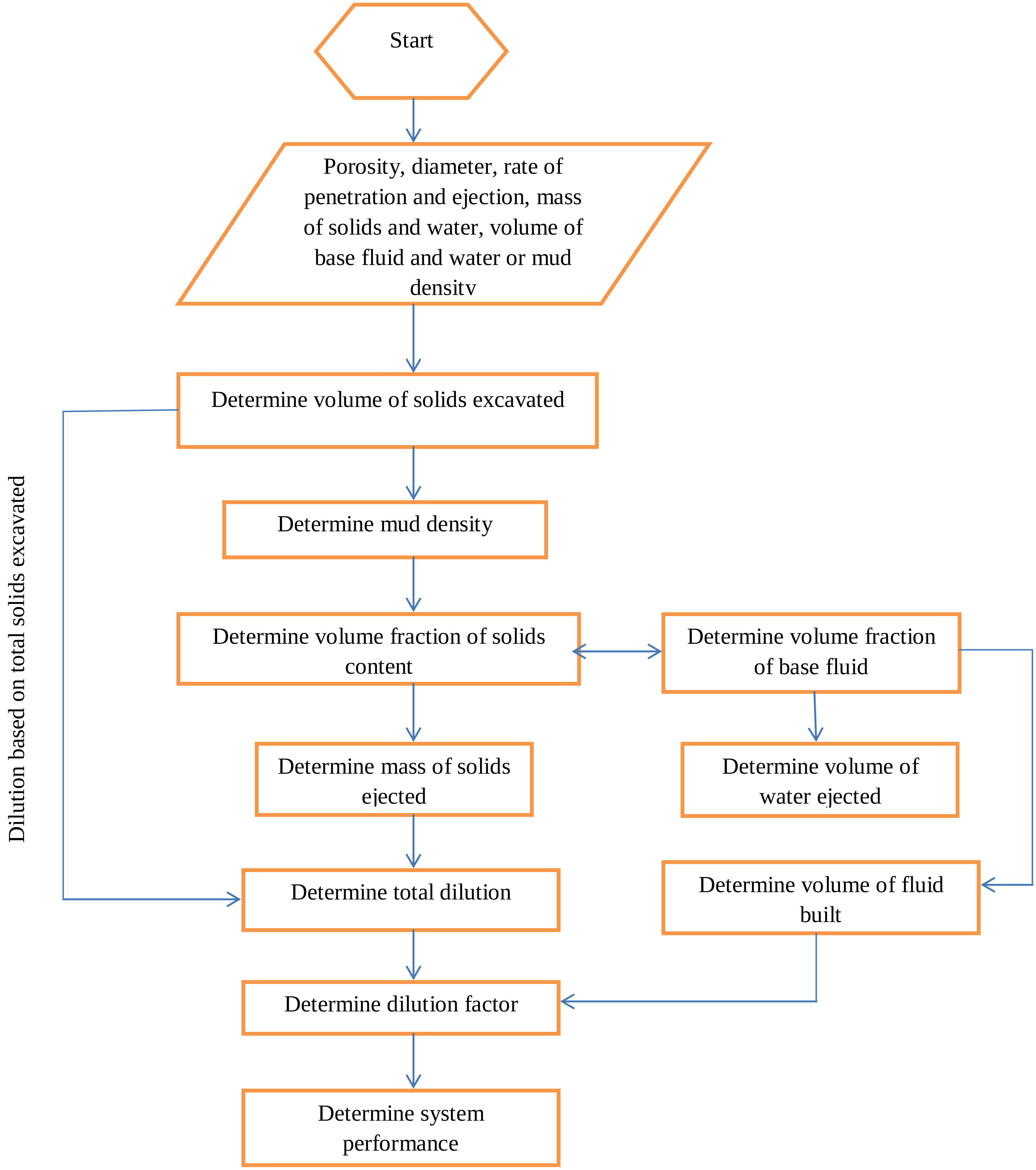

Figure 4.4: A flowchart of unweighted mud

4.2.2 Solids Control for Weighted Muds

Equations from Advanced Drilling Engineering

Centrifuge Analysis

Assumptions

- Flow rate of overflow is the sum of the mud flow rate and water flow rate into the centrifuge less the underflow rate.
- The mass rate into the centrifuge is equal the mass rate out of the centrifuge.
- Perfect mixing of the feed mud and dilution water in the centrifuge

Figure 4.5 and 4.6 shows the flowchart and the interface of weighted muds

4.2.2.1 Flowrates Involving the Centrifuge

$$q_o = q_m + q_{w1} - q_u \qquad 4.11$$

$$mass\ rate\ in = q_{w1}\rho_m + q_m\rho_m \qquad 4.12$$

$$mass\ rate\ out = q_u\rho_u + q_o\rho_o \qquad 4.13$$

$$q_w\rho_w + q_m\rho_m = q_u\rho_u + q_o\rho_o \qquad 4.14$$

$$q_u = \frac{q_m(\rho_m - \rho_o) - q_{w1}(\rho_o - \rho_w)}{(\rho_u - \rho_o)} \qquad 4.15$$

q_o = overflow rate, gal/min

q_u = underflow rate, gal/min

q_{w1} =water flow rate, gal/min

p_o =density of overflow, lbm/gal

p_u=density of underflow, lbm/gal

p_w =density of water, lbm/gal

4.2.2.2 Mass Rate of Clay and Additives

$$\rho_u = \rho_m f_{um} + \rho_w f_{uw} + \rho_B f_{uB} \quad 4.16$$

$$f_{uw} = f_{um} \cdot \frac{q_{w1}}{q_m} \quad 4.17$$

$$f_{uB} = 1 - f_{um} - f_{uw} = 1 - f_{um} - f_{um}\frac{q_{w1}}{q_m} \quad 4.18$$

$$f_{um} = \frac{(\rho_B - \rho_u)}{\rho_B - \rho_m + \frac{q_{w1}}{q_m}(\rho_B - \rho_w)} \quad 4.19$$

f_{um} = volume fraction of underflow mud

f_{uw} = volume fraction of dilution water in underflow stream

f_{uB} = volume fraction of API barite in underflow stream

p_B =density of barite, lbm/gal

4.2.2.3 Flowrates into the Mixing Pit

$$f_m = \frac{q_u f_{um}}{q_m} \quad 4.20$$

$$w_i = c_i q_m (1 - f_m) = c_i (q_m - q_u f_{um}) \quad 4.21$$

f_m = volume fraction of old mud

c_i = desired concentration of Wyoming bentonite, deflocculants and additives

w_i = mass rate of desired concentration of Wyoming bentonite, deflocculants and additives

$$q_m = q_u + q_{w2} + \frac{w_B}{\rho_B} + \frac{w_c}{\rho_c} + \sum_{i=1}^{n} \frac{w_i}{\rho_i}$$

$$q_m \rho_m = q_u \rho_u + q_{w2} \rho_w + w_B + w_c + \sum_{i=1}^{n} w_i \quad 4.22$$

Combining equation 22 and 23,

$$q_{w2} = \left[q_m(\rho_B - \rho_m) - q_u(\rho_B - \rho_u) - w_c\left(\frac{\rho_B}{\rho_c} - 1\right) - \sum_{i=1}^{n} w_i\left(\frac{\rho_B}{\rho_i} - 1\right) \right] \div (\rho_B - \rho_w) \quad 4.23$$

$$w_B = \left(q_m - q_u - q_{w2} - \frac{w_c}{\rho_c} - \sum_{i=1}^{n} \frac{w_i}{\rho_c} \right) \rho_B \quad 4.24$$

q_{w2} = water flow rate into the mixing pit, gal/min

w_B = mass flow rate of barite into the mixing pit, lbm/min

4.2.2.4 Solids Content Determination

$$\rho_m = \rho_w f_w + \rho_{lg} f_{lg} + \rho_B f_B + \rho_o f_o \quad 4.25$$

$$f_B = 1 - f_w - f_{lg} - f_o \quad 4.26$$

Combining equation 26 and 27,

$$f_{lg} = \frac{\rho_w f_w + (1 - f_o - f_w)\rho_B + \rho_o f_o - \rho_m}{\rho_B - \rho_{lg}} \quad 4.27$$

Freshwater muds without oil

$$f_s = \frac{\rho_m + f_{lg}(\rho_B - \rho_{lg}) - \rho_w}{\rho_B - \rho_w} \qquad 4.28$$

ρ_{lg} = density of low gravity solids, lbm/gal

ρ_o = density of oil in the mud, lbm/gal

f_{lg} = volume fraction of low gravity solids

f_w = volume fraction of water present

f_o = volume fraction of oil in the mud.

4.2.2.5 Quality of Low Gravity Solids in Drilling Fluid

The measurement from cation exchange capacity using the methylene blue is employed here.

$$Z_{vm} = 100mL\left(f_c\rho_c \cdot \frac{Z_{vc}}{100} + f_{ds}\rho_{ds} \cdot \frac{Z_{vds}}{100}\right) \qquad 4.29$$

Assuming the ρ_c and ρ_{ds} are approximately 2.6 g/mL, equation (29) becomes;

$$Z_{vm} = 2.6(f_c Z_{vc} + f_{ds} Z_{vds}) \qquad 4.30$$

$$f_{lg} = f_{ds} + f_c$$

$$f_c = \frac{Z_{vm} - 2.6 f_{lg} Z_{vds}}{2.6(Z_{vc} - Z_{vds})} \qquad 4.31$$

Z_{vm} = cation exchange capacity of mud in meq/100 ml of mud sample

Z_{vc} = cation exchange capacity of bentonite clay, meq/100 ml

Z_{vds} = cation exchange capacity of drilled solids, meq/100 ml

f_c = bentonite clay fraction

f_{ds} = drilled solids fraction

p_c = density of bentonite, lbm/gal

p_{ds} = density of drilled solids, lbm/gal

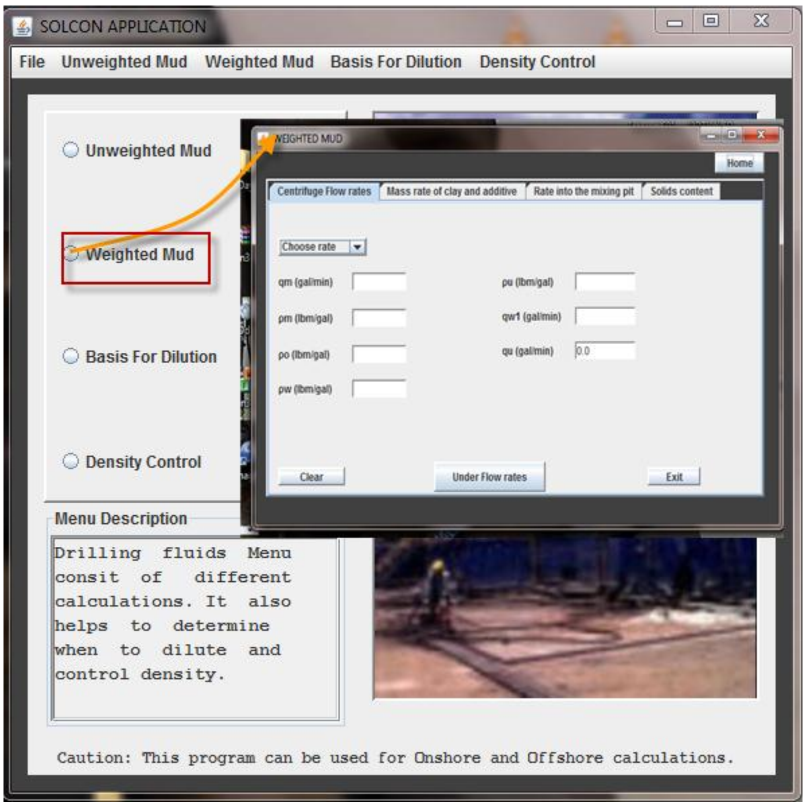

Figure 4.5: An interface showing weighted mud calculation

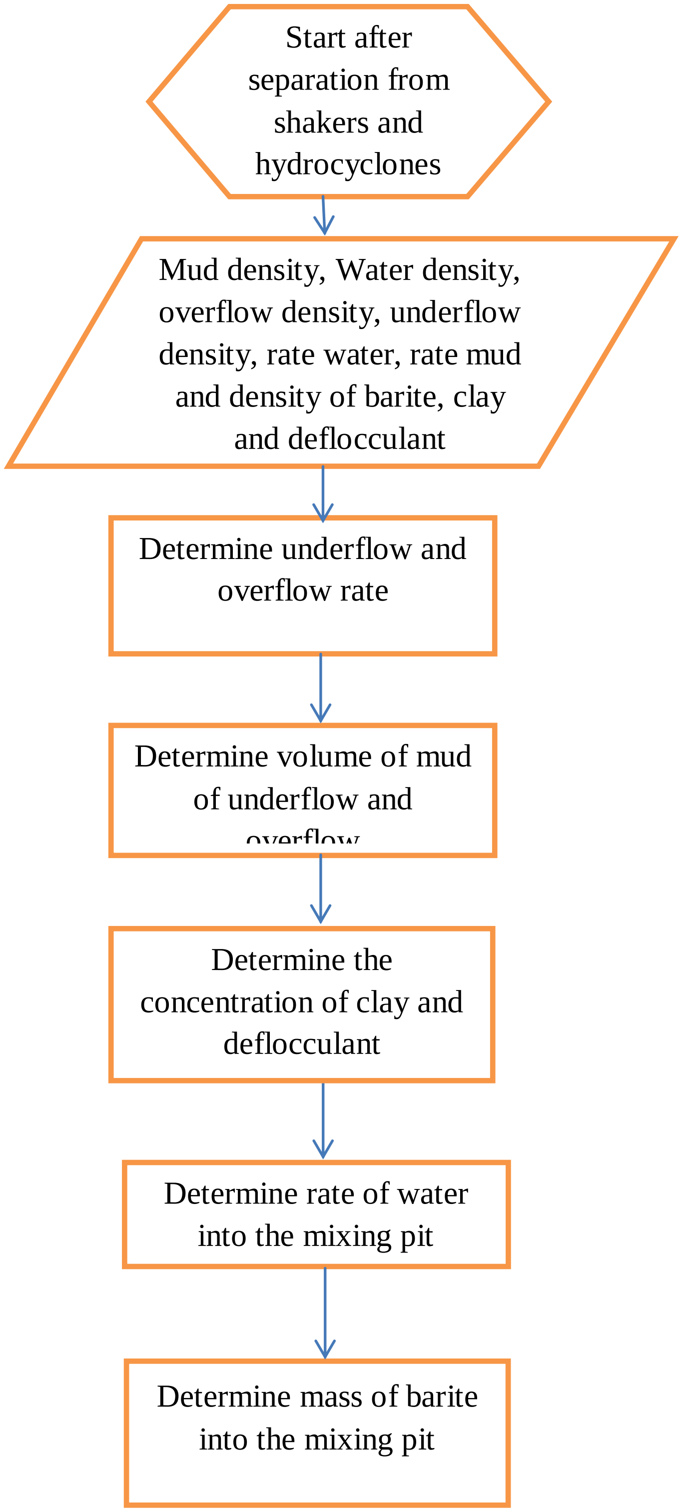

Figure 4.6: A flowchart of weighted mud

4.2.3 Basis for dilution

Figure 4.7 and 4.8 shows the interface for calculating dilution constraints and whether to dilute or not and the flowchart for basis for dilution. The dashed lines shows alternate basis for dilution.

4.2.3.1 Dilution Based on Fraction of Drilled Solids (f_{ds}) and Recommended Solids (f_{sr})

$f_{lg} = \frac{f_s - 0.3125\left(\frac{\rho_m}{8.33} - 1\right)}{0.5}$ From equation (29)

f_c from equation (32)

$f_{ds} = f_{flg} - f_c$

If the maximum f_{ds} (f_{dsmax}) is exceeded, dilution is done to reduce the drilled solid content. f_{dsmax} is usually based on company policy and there are no drilled solids volume fraction specifications, dilution can be based on recommended solids content fsr from equation (34) i.e. if the actual measured or calculated f_s is greater than f_{sr}.

From correlation

$$f_{sr} = 2.965\rho_m - 14.89 \quad 4.32$$

Assuming a limited volume

$$V_2 = V_1 + V_w + \frac{m_B}{\rho_B} \quad 4.A$$

$$\rho_2 V_2 = \rho_1 V_1 + \rho_w V_w + m_B \quad 4.B$$

$$f_{dsmax}V_2 = f_{ds}V_1 \quad 4.C$$

From equation AB and C

$$V_1 = V_2 \frac{f_{dsmax}}{f_{ds}} \quad 4.33$$

Volume to be discarded

$$Discard = V_2 - V_1 \quad 4.34$$

Dilution volume of water required

$$V_w = \frac{(\rho_B - \rho_2)V_2 - (\rho_B - \rho_1)V_1}{(\rho_B - \rho_w)} \quad 4.35$$

Amount of barite to be added after dilution

$$m_B = (V_2 - V_1 - V_w)\rho_B \quad 4.36$$

V_1 = initial volume of mud, bbl

V_2 = present volume of mud, bbl

V_w = volume water required, bbl

ρ_1 = density of initial mud, lbm/gal

ρ_2 = density of present mud, gal/lbm

m_B = mass of barite, lbm

f_{dsmax} = maximum allowable drilled solids

f_{sr} = recommended solids content

4.2.3.2 Chemical Upgrading

The assumption is chemical concentration before dilution = concentration after dilution

Limited volume

$$Concentration\ after = \frac{chemical\ after\ discard\ \&\ dilution + chemical\ added}{initial\ volume}$$

$$chemical\ before = V_1 C_1$$

$$chemical\ after\ discard\ \&\ dilution = V_1 C_1 - DC_1$$

$$concentration\ after = \frac{V_1 C_1 - DC_1 + m}{V_1} = C_1 \qquad 4.37$$

$$m = DC_1 \qquad 4.38$$

Unlimited volume

$$volume\ of\ solution\ after\ dilution = V_1 + w$$

$$Amount\ of\ chemical\ after\ making\ up = V_1 C_1 + m$$

From the above assumption,

$$C_1 = \frac{V_1 C_1 + m}{V_1 + w} \qquad 4.39$$

$$m = C_1 m \qquad 4.40$$

C_1 = concentration before dilution, g/bbl

D = volume mud of discarded, bbl

m = amount of chemical added, g

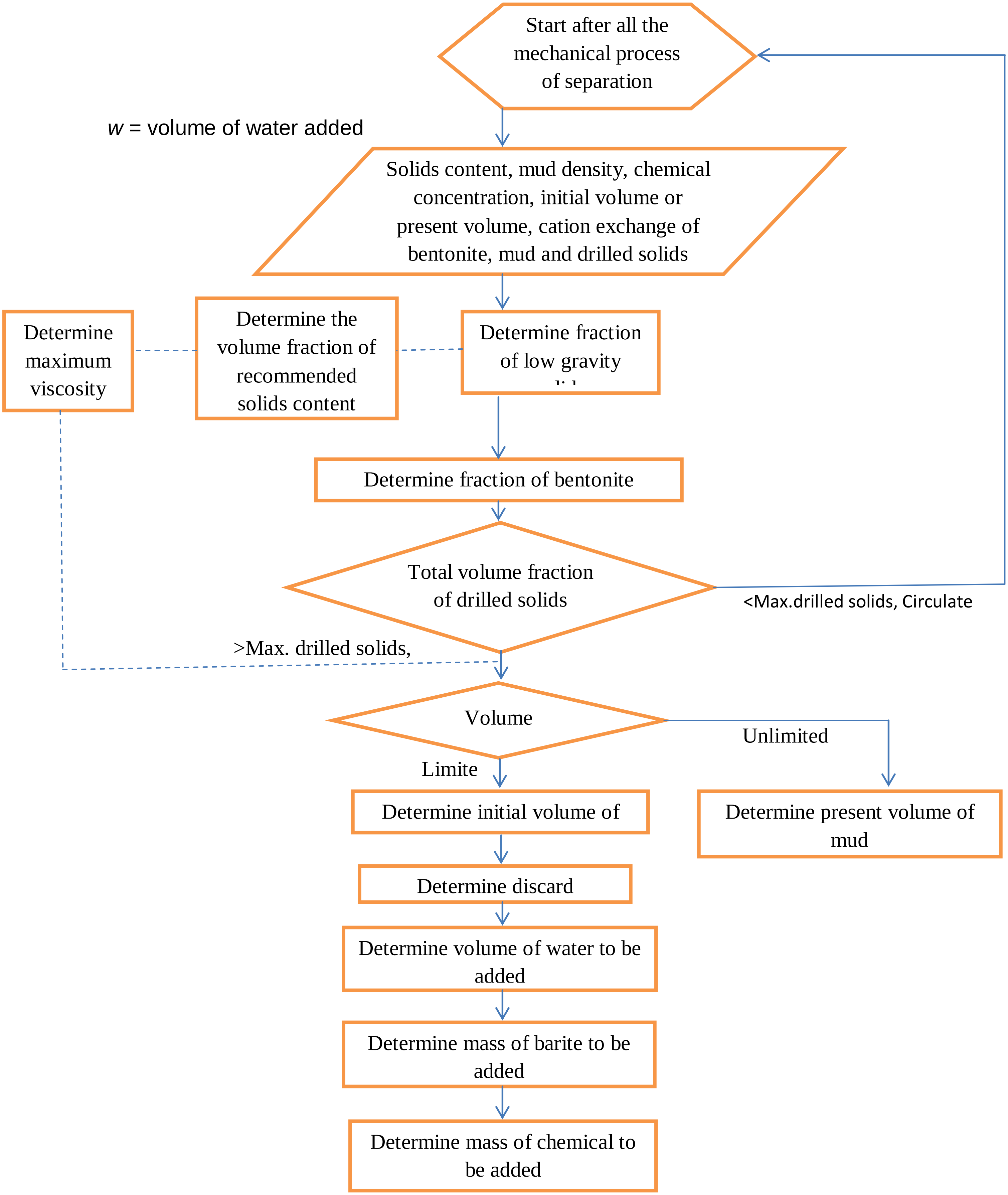

Figure 4.7: A flowchart of Basis for Dilution

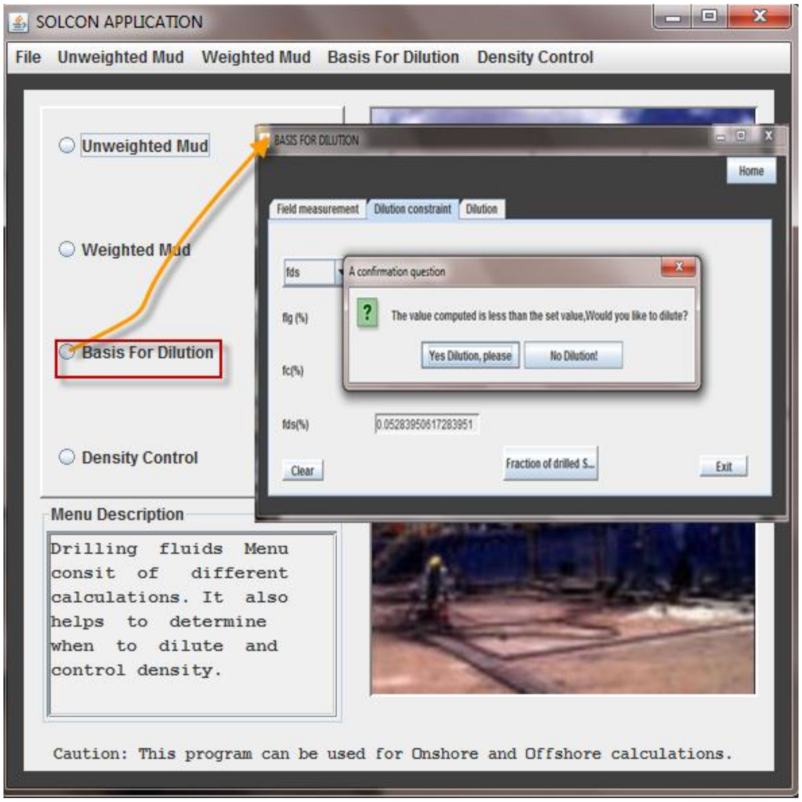

Figure 4.8: An interface showing Basis for Dilution calculation

4.2.3.2 Dilution Based on Viscosity

From correlation

$$\mu_{max} = 3.022^{0.162\rho_m} \qquad 4.41$$

Compare the value from equation (39) with the actual measured viscosity value of mud.

If the measured value is greater than the μ_{max}, then dilute based on the steps in section 4.2.4

μ_{max} = maximum allowable viscosity, cp

4.2.4 Density Control

The densities of the mud have to be upgraded to its previous state before recirculating the mud into the hole to continue drilling. Figure 4.9: shows an interface showing Density Control calculation

4.2.4.1 Addition of Barite

$$V_2 = V_1 + \frac{m_B}{\rho_B} \qquad 4.D$$

$$V_2\rho_2 = \rho_1 V_1 + m_B \qquad 4.E$$

From equation D and E

$$V_1 = V_2 \frac{(\rho_B - \rho_2)}{(\rho_B - \rho_1)} \quad limited\ mud\ volume \qquad 4.42$$

$$V_2 = V_1 \frac{(\rho_B - \rho_1)}{(\rho_B - \rho_2)} \quad unlimited\ mud\ volume$$

$$m_B = (V_2 - V_1)\rho_{\boldsymbol{B}} \qquad 4.43$$

4.2.4.2 Addition of Barite with Water

$$V_2 = V_1 + \frac{m_B}{\rho_B} + m_B V_{wB} \qquad 4.F$$

$$\rho_2 V_2 = \rho_1 V_1 + \rho_w m_B v_{wB} \qquad 4.G$$

From equation F and G

$$V_1 = V_2 \left[\frac{\rho_B\left(\frac{1+\rho_W v_{wB}}{1+\rho_B V_{wB}}\right)-\rho_2}{\rho_B\left(\frac{1+\rho_W V_{wB}}{1+\rho_B V_{wB}}\right)-\rho_1} \right] \ limited\ mud\ volume \qquad 4.44$$

$$V_2 = V_1 \left[\frac{\rho_B\left(\frac{1+\rho_W v_{wB}}{1+\rho_B V_{wB}}\right)-\rho_1}{\rho_B\left(\frac{1+\rho_W V_{wB}}{1+\rho_B V_{wB}}\right)-\rho_2} \right] \ unlimited\ mud\ volume$$

$$m_B = \frac{\rho_B}{1+\rho_B V_{wB}} (V_2 - V_1) \qquad 4.45$$

V_{wB} = addition ratio water and barite, gal/lbm sack

4.2.4.3 Efficiency Calculation

Equipment solid removal efficiency (ESRE)

$$ESRE = \frac{Volume\ of\ drilled\ solids\ discarded}{Volume\ of\ drilled\ solids\ \ arriving\ @\ the\ surface} \qquad 4.46$$

Optimum solids removal efficiency (Opt SRE)

$$Opt\ SRE = \frac{1-T_{sf}}{(1-T_s)+\frac{T_{sf}}{S_{cd}}} \qquad 4.47$$

T_{sd} = targeted drilled solids concentration in drilling fluid

S_{cd} = targeted drilled solids concentration in discards

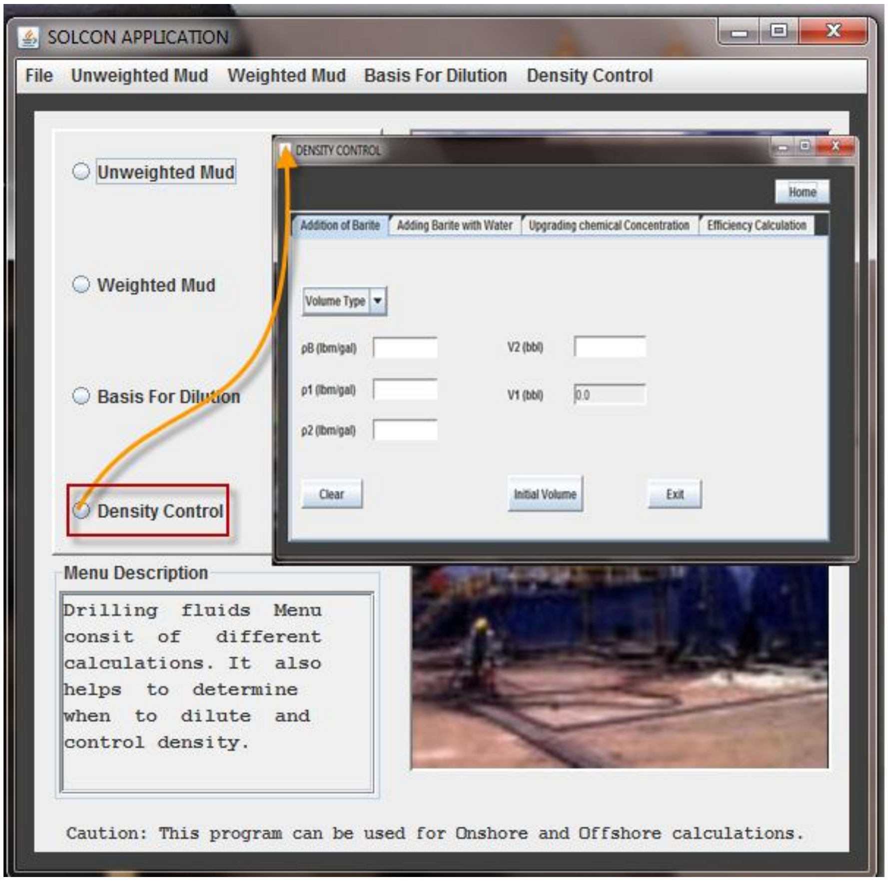

Figure 4.9: An interface showing Density Control calculation

4.3 Results and Discussion

SOLCON was validated using examples from Advanced Drilling Engineering text book. Given 15in, 25% and 100ft/hr as diameter, porosity and rate of penetration for unweighted mud the total volume excavated, Vs is 16.4 bbl/hr and Fig 4.10 shows the result obtained from SOLCON. For weighted mud, given the following parameters, qw1 = 10.57 gal/min, qm = 16.53 gal/min, Pu = 23.4 lbm/gal, Po= 9.3 lbm/gal, Pm = 16. 2 lbm/gal, Pw = 8.33 lbm/gal, pB = 35 lbm/gal, volume and density of bentonite and deflocculant is 22.5 lbm/bbl, 6 lbm/bbl and 21.7 lbm/gal. 7.36 gal/min, 32.4%, 7.58 lbm/min, 2.02 lbm/min, 8.23 gal/min and 17.4 lbm/min are the results calculated for underflow rate, underflow volume fraction of mud, concentration of bentonite, concentration of deflocculant, water flow rate and mass rate of barite into the mixing pit while Fig 4.11 shows the results obtained from SOLCON.

4.3.1 Sensitivity Analysis

SOLCON was flexibly designed such that with changing parameters, corresponding results will be obtained. This was confirmed by changing the mud density in the example in section 4.3 to see the combined effect it has on underflow rate, water flowrate and mass rate of barite into the mixing pit. The results obtained are demonstrated in the figures below.

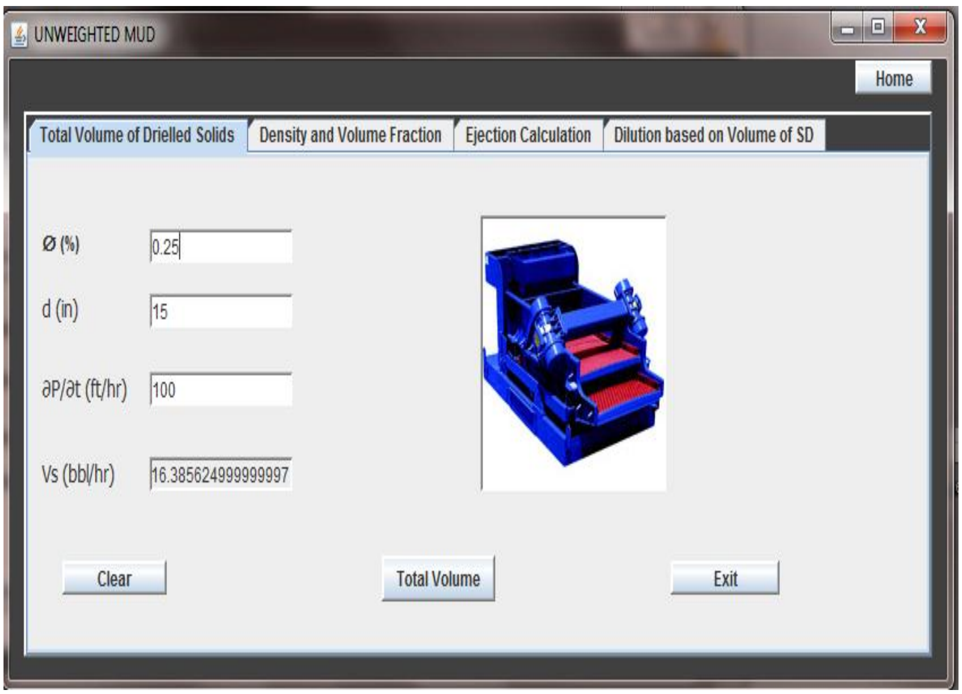

Figure 4.10: SOLCON computed value for V_s

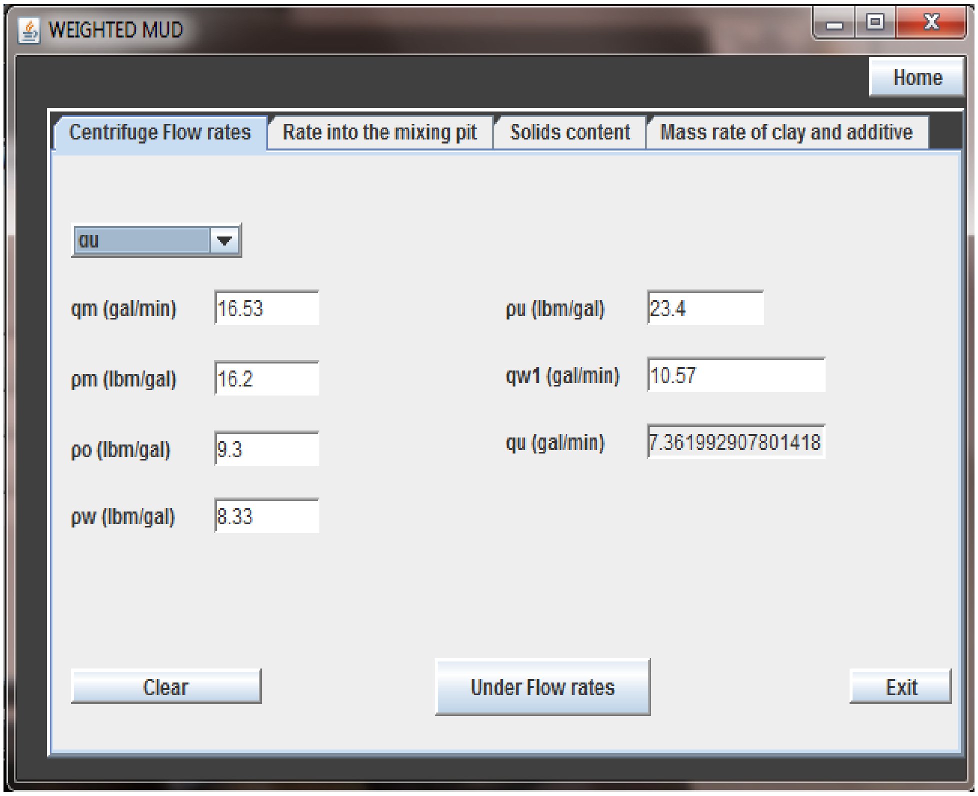

Figure 4.11: SOLCON computed value for q_u

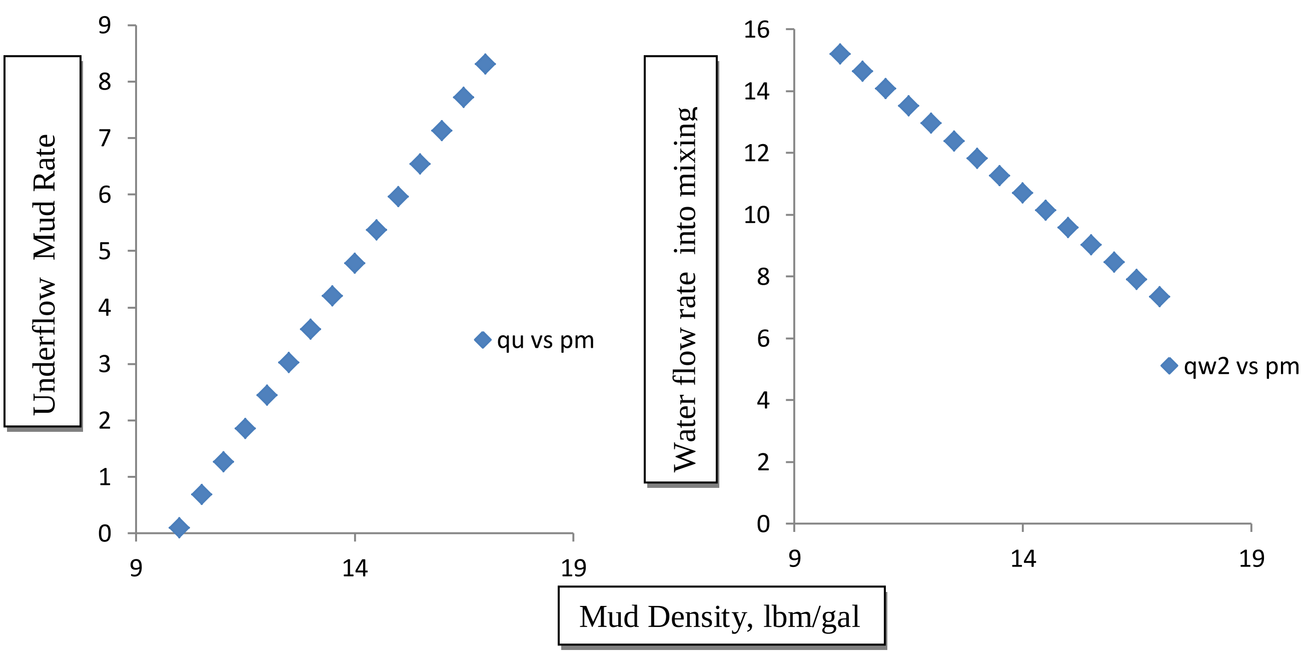

Figure 4.12: Underflow rate and water flowrate into the mixing pit plotted against mud density

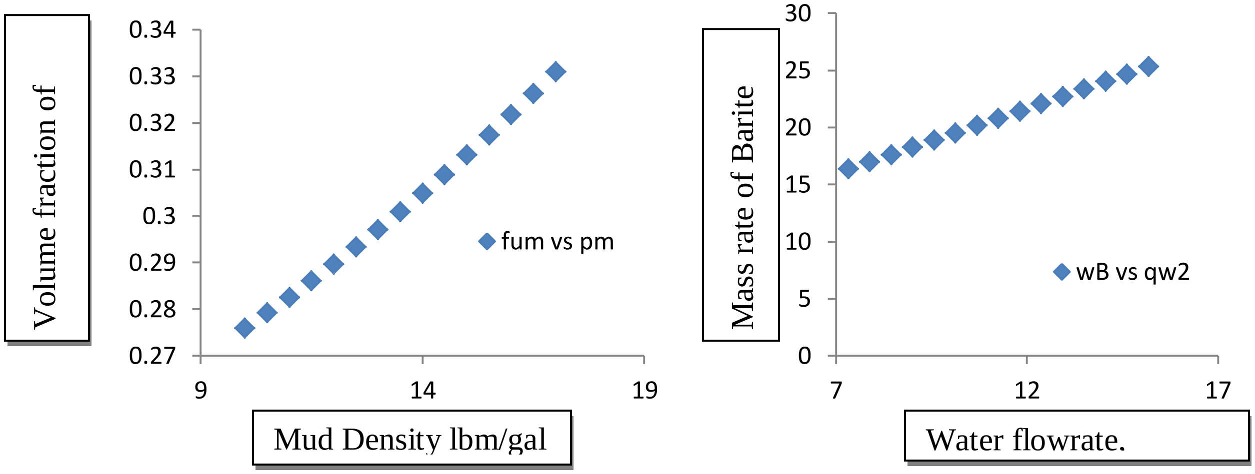

Figure 4.13: Volume fraction against mud density and mass rate of barite against water rate

The plots obtained show the exact relationship between mud density and the other parameters from equations. For optimum drilled solids removal efficiency, Fig 4.14 shows how the system behaves as the percentage concentration of targeted drilled solids in discard changes while Fig 4.15 shows the behaviour as the percentage concentration of targeted drilled solids in the drilling fluid changes.

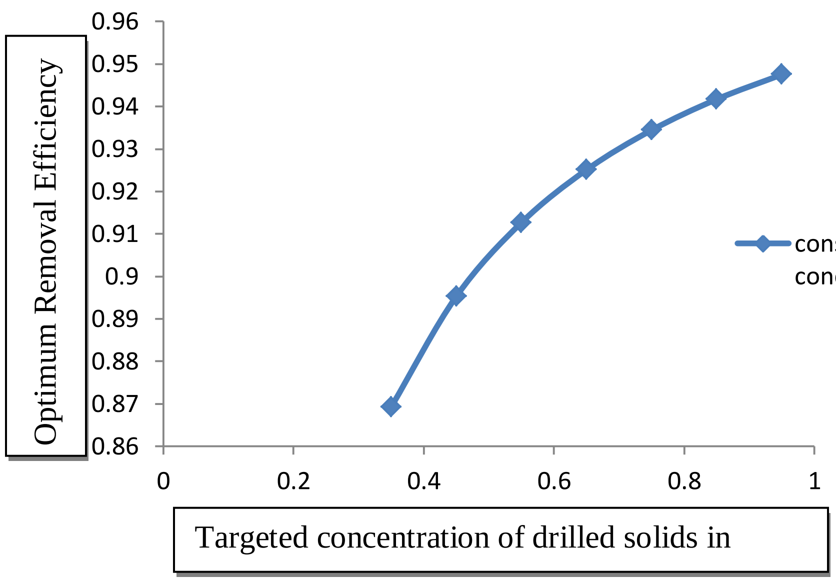

Figure 4.14: Optimum drilled solids removal efficiency against drilled solids in discards

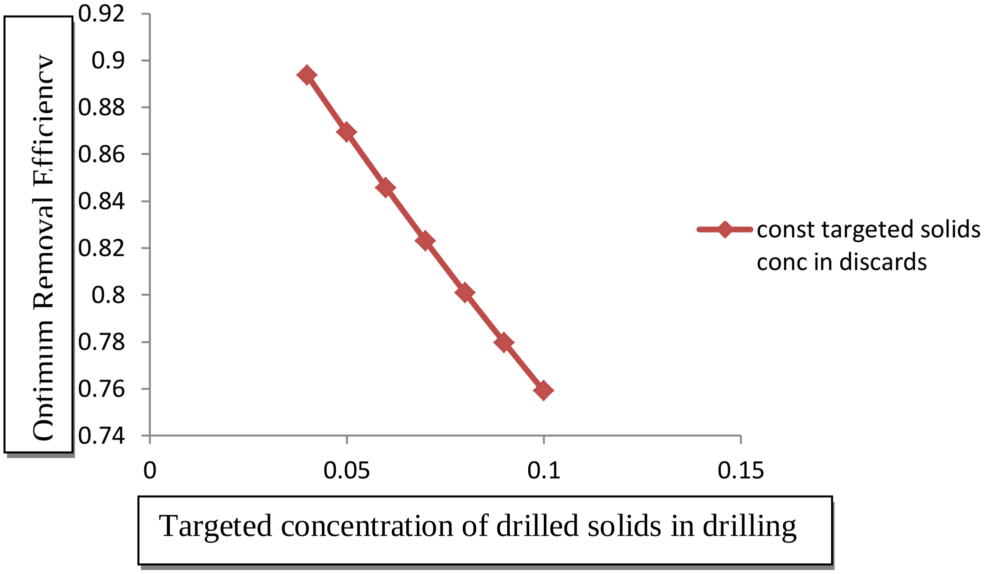

Figure 4.15: Optimum drilled solids removal efficiency against drilled solids in fluid

4.3.2 Analysis of Entrained Drilled Solids after Routine Solids Control

Despite all the innovation made in solids control system, it is a documented fact that the solid control equipment does not remove all entrained solids. Some of these solids will eventually get recirculated. The effect of these entrained solids has been discussed earlier in section 2.7. In this section we attempt to quantify the amount of drilled solids that could evade removal by conventional equipment. From some correlations from Bourgoyne et al., 1986 connecting these correlations to the understanding of the separation process and operation of the mechanical equipment; we have been able to deduce the volume fraction of solids that will remain in the drilling fluid and recirculated depending on the shaker's mesh size (150 and 200). This table was generated using Microsoft excel spread sheet.

The first column in the analysis is the standard drilled solid sizes in the mud which was derived from Fig 2.1 and 2.3. It must be noted that the proportion of drilled solids depends on the formation drilled and the drilling parameters. The following columns are the percentages of drilled solids evading the shale shaker, desander of 6 in diameter, desilter of 4 in diameter and centrifuge. The last column is the unremoved drilled solids fraction which is the aggregate or the multiple of solids fraction evading removal at each solids control equipment.

It can be seen from the Table 4.1 and 4.2 that using the 200 mesh size allow less drilled solids to be recirculated when compared to the 150 mesh size shale shaker as should be expected. When realistic value is available for different capacities of the basic solids control equipment, it is possible to optimize the selection of the separation equipment combination. The summation of the individual unremoved drilled solids in the final column of the table gives the volume fraction of the drilled solids being recirculated. Using these values, one can easily calculate the actual volume of solids going back into the system.

Table 4.1: Analysis of Entrained Drilled Solids after Routine Solids Control for 150 Mesh Size shale shaker

Vs(bbl/hr)	Size Microns	% DrilledSolids	Shaker, 150	Desander (6")	Desilter (4")	Centrifuge	% of Unremoved solids	Unremoved solids with specified volume
16.38453	5	0.375	1	0.03	0.92	0	0	0
	10	0.035	1	0.04	0.9	0.9	0.001134	0.018580057
	20	0.135	1	0.9	0.5	0.5	0.030375	0.497680093
	30	0.045	1	0.75	0.23	0.23	0.001785375	0.02925253
	40	0.05	1	0.5	0.15	0.15	0.0005625	0.009216298
	50	0.04	1	0.35	0.05	0.05	0.000035	0.000573459
	60	0.023	1	0.25	1	1	0.00575	0.094211046
	70	0.012	1	0.19	1	1	0.00228	0.037356728
	80	0.015	1	0.12	1	1	0.0018	0.029492154
	90	0.01	1	0.08	1	1	0.0008	0.013107624
	100	0.01	0	0	0	0	0	0
	200	0.025	0	0	0	0	0	0
	300	0.025	0	0	0	0	0	0
	400	0.025	0	0	0	0	0	0
	500	0.018	0	0	0	0	0	0
	600	0.018	0	0	0	0	0	0
	700	0.018	0	0	0	0	0	0
	800	0.018	0	0	0	0	0	0
	900	0.01	0	0	0	0	0	0
	1000	0.01	0	0	0	0	0	0
	10000	0.083	0	0	0	0	0	0
Total							0.044521875	0.729469988

Table 4.2: Analysis of Entrained Drilled Solids after Routine Solids Control for 200 Mesh Size shale shaker

Vs(bbl/hr)	Size, Microns	% DrilledSolids	Shaker, 200	Desander (6")	Desilter (4")	Centrifuge	% of Unremoved solids	Unremoved solids with specified volume
16.4	5	0.375	1	0.03	0.92	0	0	0
	10	0.035	1	0.04	0.9	0.9	0.001134	0.0185976
	20	0.135	1	0.9	0.5	0.5	0.030375	0.49815
	30	0.045	1	0.75	0.23	0.23	0.001785375	0.02928015
	40	0.05	1	0.5	0.15	0.15	0.0005625	0.009225
	50	0.04	1	0.35	0.05	0.05	0.000035	0.000574
	60	0.023	1	0.25	0	0	0	0
	70	0.012	0	0	0	0	0	0
	80	0.000995025	0	0	0	0	0	0
	90	0.01	0	0	0	0	0	0
	100	0.01	0	0	0	0	0	0
	1000	0.167	0	0	0	0	0	0
	10000	0.083	0	0	0	0	0	0
Total							0.033891875	0.55582675

4.3.3 Economics

The drilling process may look simple as boring hole in to the earth's formation. However, in achieving this, the process must be conducted in a safe, cost effective and environmentally friendly manner. The utilization of mechanical equipment and application of dilution at the appropriate time enables the driller to maintain the desired fluid properties. This will in turn make the drilling operation efficient and economical. Drilling fluid involves a wide range of factors that dictates the duration and the cost of drilling operation. Efficient solids control increases rate of penetration, bit life and reduces mud cost, hole problems, abrasion and pump wear. Hence it is patent that there is a relationship between control of drilled solids and total drilling cost. For instance, rig time can increase if at a constant drilling rate the bit is regrinding the drilled solids contained in the fluid instead of increasing the depth of formation being penetrated. This may not only reduce the rate of drilling and make solids removal difficult, but also put pressure on the exhaustibles such as the pump where energy is being loss.

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

The set objectives of this work is to save rig time by building a computer program to perform routine rig computations: calculations of solids content, the volume of new mud required, the amount of additives, etc. This operation is geared towards enhancing drilling efficiency. The work is therefore geared towards the review of solids control methods, development of analytical equations for solids control and finally, development and validation of a computer program to implement the routines. As a directive towards the above objectives, the different type of drilling fluids was first discussed in chapter two. Each type of drilling fluid has its specific function and type of formation and the depth of hole to be drilled. The accumulation of drilled solids in drilling fluid can retard cuttings transport, reduce rate of penetration and cause lost circulation. Chapter three re-emphasized on testing and treatment of drilling fluid. The various stages and type of solids removal equipment were also highlighted. The adequate retention time for the shale shaker, hydrocyclone and the centrifuge is an important component in solids removal efficiency. The computer program was developed in chapter four using *Java* software. The program was validated using some textbook examples from Applied Drilling Engineering and its flexibility tested by using different mud densities.

5.2 Conclusion

This work was aimed at building a computer program. We succeeded in developing interactive Java-based software, SOLCON, to control drilled solids. This software incorporates an iterative and interactive tool which would determine when to dilute and calculate the density of new mud, volume of new mud, amount of barite, bentonite and additives and solids content. It solves for the use of calculators, saves man-hours while at the same time opportune the driller to see the input values in case of any error. It is also necessary to note the software's conversion unit and hence the unit of the input data.

5.3 Recommendation

- More practical research should be carried on the solids removal process so as to develop a computer program that will simulate the retention time, mesh size, and force of agitation depending on the type of solids and formation being drilled.
- A comprehensive economic study should be done to determine in figures how much is being saved from efficient solids control of drilling fluid. This would help quantify the relationship between economics and control solids.

NOMENCLATURE

μ_{max} = maximum allowable viscosity

ρ = density of mud

ρ_1 = density of initial mud

ρ_2 = density of present mud

ρ_B =density of barite

ρ_c = density of bentonite

ρ_{ds} = density of drilled solids

ρ_{lg} = density of low gravity solids

ρ_o = density of oil in the mud

ρ_o = density of overflow

ρ_s = density of drilled solids

ρ_u = density of underflow

ρ_w =density of water

ρ_w = density of water

φ = porosity

c_i = desired concentration of Wyoming bentonite, deflocculants and additives

C_1 = concentration before dilution

D = volume mud of discarded

D_t = Total dilution

D_F = Dilution factor

d = diameter

ESRE = Equipment solid removal efficiency

f_{bf} = volume fraction of base fluid

f_c = bentonite clay fraction

f_{ds} = drilled solids fraction

f_{dsmax} = maximum allowable drilled solids

f_{lg} = volume fraction of low gravity solids

f_m = volume fraction of old mud

f_o = volume fraction of oil in the mud.

f_s = volume fraction of solids

f_{sr} = recommended solids content

f_{uB} = volume fraction of API barite in underflow stream

f_{um} = volume fraction of underflow mud

f_{uw} = volume fraction of dilution water in underflow stream

f_w = volume fraction of water

f_w = volume fraction of water present

m = amount of chemical added

m_B = mass of barite

m_{se} = mass rate of solids ejected

m_s = mass of solids excavated

m_w = mass of water in the mud

Opt SRE = Optimum solids removal efficiency

r = rate of ejection of slurry (volume/time)

S_{cd} = targeted drilled solids concentration in discards

SP = system performance

T_{sd} = targeted drilled solids concentration in drilling fluid

q_o = overflow rate

q_u = underflow rate

q_{w1} = water flow rate

q_{w2} = water flow rate into the mixing pit

V_1 = initial volume of mud

V_2 = present volume of mud

V_{bf} = volume base fluid added or volume fluid discarded

V_{mb} = Drilling fluid built

V_s = Total volume of drilled solids excavated

V_w = volume water required

V_w = volume of water in the mud

V_{wB} = addition ratio water and barite

V_{we} = volume rate of water ejected

w = volume of water added

w_B = mass flow rate of barite into the mixing pit

w_i = mass rate of desired concentration of Wyoming bentonite, deflocculants and additives

Z_{vc} = cation exchange capacity of bentonite clay

Z_{vds} = cation exchange capacity of drilled solids

Z_{vm} = cation exchange capacity of mud in meq/100mL of mud sample

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