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AI Enabled Software Program to Help Calculate Shear Stress of Drilling Fluid at Realistic Bottomhole Conditions

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Abstract

The rheology of drilling fluids is presently being measured with the help of a rotational viscometer that facilitates the measurements at laboratory conditions, (that also on fixed RPMs) which are not the same as bottomhole conditions. In order to obtain a more accurate value of shear stress at any given shear rate, a new software program has been developed with the help of data generated by a formula, devised and validated by AI calculations. The non-Newtonian rheological behaviour of Non-Aqueous and Aqueous drilling fluid is fundamentally different and hence, two such programs have been generated, one each for aqueous and non-aqueous fluids respectively.

The values obtained represent RMSE as high as >98%. However, considering some of the intangible variable that cannot be quantified, but do alter the shear stress, the values calculated are being claimed to be only ±95% accurate. These values cannot and should not be compared and validated with the measured values currently in use, for the simple reason that the measurement and calculation conditions are different and incomparable.

A new concept of Knnamponity is being introduced to characterize the extent of Newtonian character in non-aqueous fluid, although predominantly these fluids exhibit non-Newtonian character only. Non-Newtonian fluids exhibit non-Newtonian character by viscoelasticity, unlike thixotropy, the property responsible for aqueous drilling fluids and the same has been suitably amalgamated for comparative assessment of rheological properties of aqueous and non-aqueous fluids, when compared with each other. The cuttings removal efficiency of the system has also been predicted.

Introduction

The work under consideration has been carried out for field engineers' convenience and hence one has to view it with the background of realistic field management practices prevailing in the industry on a drilling rig.

The role of drilling fluids rheology in the drilling campaign doesn't require elaborate description, and is an established feature of the drilling process. The method(s) adopted in the field to monitor the rheology of the drilling fluid and to make the desired changes are based upon the measurements of shear stress of the fluid at different shear rates which are then used to calculate the plastic viscosity and yield point of the fluid, which in turn, forms the basis of deciding the quality of the fluid. The quality of the fluid is based on the efficiency of the fluid, of which, bringing cuttings to surface is one of the most important functions and that is directly linked with rheology of the fluid.

With the passage of time, many advancements have taken place in this process. Introduction of "n" and "K" as two indices to evaluate the rheology is an example of these advancements. A rotational viscometer is popularly used on drilling rigs to measure rheology. The industry has become very much accustomed to this practice that we often either do not realize or sometimes ignore the anomalies associated with it. Following are the distinct shortcomings as well as uncertainties in the measurements of rotational viscometer:

- The rotational viscometer measures the shear stress of the fluid at a pre-decided temperature, as per the API guidelines, whereas the fluid experiences different temperature regime inside the hole, which keeps changing as the fluid moves through different depths.
- The gap between the rotor and the stator of the rotational viscometer is fixed, whereas in real case, the gap keeps changing as the fluid traverses through annuli of different diameters.
- The flow pattern of the fluid inside the hole is vertical or inclined, depending upon the trajectory of the hole, whereas the fluid experiences circular concentric motion in the rotational viscometer.
- The fluid travels in the hole with the drill cuttings which alters its shear stress, where as the fluid in the rotational viscometer is free from drilled cuttings. The Rev dust or other solids are not so big in size as drilled cuttings and hence are not considered synonymous with drilled solids.
- Rheometers have the inherent tendency to retain the memory of the previous measurement(s) to a small extent and that affects the subsequent measurement(s), allowing a room for error in the measurements to creep.
- Rheometers need periodical calibration, which is a subject of personal judgement as to when do we need to recalibrate. Even if we adhere to a periodical calibration system, yet the rheometer can lose calibration prior to that also. In real cases of field

management, it is an open secret that doesn't need elaboration as to how often do we calibrate a rheometer!

- At times the rheology of the fluid is too high for the viscometer to measure and we simply term that as OOR (Out of Range). In most cases it doesn't matter but yet, it definitely limits us in terms of knowing the exact value of shear stress and its consequences.
- The rotational viscometer puts a restriction in terms of facilitating the shear stress only at fixed RPMs. Although again, it works for the majority of the cases because we have circumvented our measurements around those shear rates with an assumption that it matches with the flow of fluid inside the annulus – a big assumption!
- The rheology of the fluid was always focused on the concept that the fluid is water-based and subsequently, with the introduction of oil-based drilling fluid, we borrowed those concepts for oil-based drilling fluid despite knowing well that both the fluids don't obey the same laws of science, as far as their rheological behavior is concerned.
- These issues have further added to the uncertainties of the rheological measurements of oil-based drilling fluid to the extent that the magnitude of error/anomaly /uncertainty of measurement(s) has increased to the extent that it shows up in the form of inadequate hole cleaning.

As drilling advanced in difficult trajectory wells and hostile bottomhole conditions, be it extremely low temperature in ultra-deepwater or in the ultra-HTHP/geothermal environment, the magnitude of error has reached a level, where the rheological measurements become arbitrary enough to not to represent the real flow behavior of the fluid, when checked with a rotational viscometer.

These facts, along with the equally bigger objective of defining the flow pattern of oil-based drilling fluid more accurately, has laid the foundation for the work undertaken, that has resulted into the development of a software model which has following advantages over the current method of shear stress measurement in field:

- The software model conspicuously provides shear stress data separately for oil-based, as well as water-based drilling fluids which is not possible by a rheometer.
- The software takes input from real-time values which affect the shear stress of the fluid under question, such as:
    - Annular velocity
    - Hydraulic diameter
    - Composition of the fluid, including clay content, corrected solids, fluid content (oil/water ratio)
    - BHCT

The larger objective is to calculate the shear stress under those conditions that exist in reality in the field.

Description of the Process

After having clearly understood the root cause of anomalies/uncertainties/short-comings, the next obvious step was to find a workable solution to each of the anomalies cited above.

- The error creeping in measurement due to pre-decided temperature measurement has been addressed by incorporating the value of BHCT in the formula for calculating the shear stress.
- Rotor/stator gap anomaly has been addressed by incorporating the hydraulic diameter as a variable that enables the calculation of shear stress. A finite upper and lower range of hydraulic diameter has been incorporated and the inter-relationship between hydraulic diameter with other variables have been clearly defined. For example, if the hydraulic diameter is large, then the BHCT shall vary between a finite range that will be less than the BHCT of a case where hydraulic diameter is smaller. This is in line with the field observation as well as the scientific fact that temperature increases as the depth increases and hydraulic diameter decreases as the depth increases. Similar treatment has been meted with all the variables, that find a place in the formula.
- Variation due to the type of drilling fluid has been addressed by having two sets of data, one each for water-based and oil-based drilling fluids. Thus, the calculated value of shear stress will be valid for the chosen drilling fluid system only.
- Memory retention and calibration-related aberrations do not exist as there is no need to use the instrument.
- Flow pattern of the fluid in the formula gets addressed by choosing the annular velocity that forces the fluid to move up at the selected depth.

Thus, after short-listing all the measurable variants and putting them at the right place, (numerator/denominator depending upon whether they increase or decrease the shear stress) a skeleton formula emerged, that is treated as a constant, separate for OBM and WBM, named as aqueous constant and non-aqueous constant.

In addition to that, although the variables were short-listed, it was equally important to assign a suitable weightage to each of them that justify their proportionate inclusion, in amalgamation with other variables!

To begin with, using the numerical analysis method, a crude formula emerged. The problem of the exact numerical value(s) of variable(s) vis-a-vis their extent of impact on shear stress needed regression of the numerical values of the variable(s) to actualize the results. This was a challenge which was addressed and solved by AI, with the use of multi-variate regression and machine learning techniques to "train" the formula to assign

Aqueous Fluids:

$$Shear\ Stress = 4.51881 * (Aqueous\ Constant)^{1.000799} * (Shear\ Rate)^{0.67483} \qquad \text{(Eq. 1)}$$

$$Aqueous\ Constant = \frac{7687.872 * (Hydraulic\ Diameter)^{\frac{1}{2}} * (Corrected\ Solids) * (Clay\ Content)^{\frac{1}{2}}}{(Annular\ Velocity) * BHCT * (100 - Oil\ Percentage + Corrected\ Solids)} \qquad \text{(Eq. 2)}$$

Non-Aqueous Fluids:

$$Shear\ Stress = 8.336 * (Non - Aqueous\ Constant)^{1.0021} * Shear\ Rate^{0.6942} \qquad \text{(Eq. 3)}$$

$$Non - Aqueous\ Constant = \frac{1.362 * (Hydraulic\ Diameter)^{\frac{1}{2}} * (Corrected\ Solids) * (Emulsion\ Density) * (Water\ Percentage) * Clay\ Content}{Annular\ Velocity * BHCT * Oil\ Percentage * \left(\frac{Oil\ Percentage}{Water\ Percentage}\right)^{\frac{1}{2}}} \qquad \text{(Eq. 4)}$$

correct numerical values / weightages that “fits” the entire range of all the variables. The accuracy of the weightage was determined by validating the findings by choosing the values and closely observing the uniformity of the results across the entire range of RPMs.

The weightage of each component in its individual capacity is different whereas when applied in conjunction with other variables, the outcome would be different. Since in real case, all the variables co-exist with each other, it was logical to apply the dynamic impact of each variable in presence of all the other variables. This was accomplished by choosing a finite lower and upper range with-in which the chosen variable appears in most of the cases. A large number of data (~20,000+) were generated by including all the variables with practically relevant values of each of the chosen variable with suitable correction applied to their actual values, as suggested by AIML, where-in the values were worked upon in various permutation combinations till a set of data was arrived at, that gave the most accurate output, as decided by the modelling technique. This formula was accurate ~74% because up until now, the impact of intangible variables has not been incorporated.

The most challenging part of the work was to incorporate the impact of variables that cannot be accurately quantified but they impact the shear stress, like:

- Tortuosity of the hole
- Lubricity of the fluid
- Irregularities in hydraulic diameter due to uneven hole size with the same size of the bit, as a result of mechanical, chemical, or physico-chemical forces, altering the hole diameter
- Presence of cuttings of different size and shape
- Swelling of the reactive clay portion of the drill cuttings, leading to change in clay content of the fluid in water-based drilling fluid and thus altering the shear stress
- Variation in BHCT due to intermittent static conditions in hole during the period of “no circulation” leading to a temporary increase in BHCT till it equilibrates after resumption of drilling fluid circulation

The AIML techniques were deployed to arrive at a value of shear stress that is accurate for any chosen value of shear rate, even beyond the 600 RPM level, the shear rate beyond which the rotational viscometers are incapable of measuring.

RMSE (Root mean square error) was chosen as a criterion to decide the validity of the formula and the percentage accuracy of the shear stress value calculated. It was found that for matching RMSE for both the types of drilling fluid systems, the constant values were different – another evidence of the versatility of the formula as well as the concept that aqueous and non-aqueous fluids have different rheological response even in similar conditions.

All the amalgamation, regression as guided by AIML tools, finally resulted into the emergence of the formula for respective type of drilling fluid systems. Equations 1-2 depict the formulations for aqueous drilling fluids and Equations 3-4 depict the formulas for non-aqueous drilling fluids.

The entire process of conversion of data into a software can be summarized as:

- Matplotib library in Python programming was used to visualize the data
- The dependency of various variables was determined to help process the data such that it can be easily modelled
- This revealed that Multiple regression model is the most suitable option
- Scikit learn library was used to model the data in Python programming.

By using Python, Django, Fast API, HTML and CSS, a user-friendly software has been built where the user can provide input, with the help of which the program will automatically calculate shear stress for the chosen set of data.

Figures 1-4 are sample data for explaining the process of arriving at the shear stress values for different RPMs with the help of the formula for respective type of drilling fluid system. These data included here are for representation purpose only and need not fit into the formula to give correct values of shear stress at selected shear rate. The same also holds good for the formulae included in the paper.

Cuttings Removal

The study also addresses the situation of hole cleaning by predicting the cuttings removal efficiency of the system with the input from shear stress value at 300 RPM, separately for aqueous and non-aqueous drilling fluid systems. The value of 300 RPM has been chosen as the shear rate for the reason that in majority of the cases the shear stress of the fluid inside the hole can be considered close to 300 RPM, apart from BHA area and the bit nozzles. This selection has a bias of so many years of industry usage of 600 and 300 RPM values as data for defining the rheology.

BHA area invariably experiences turbulent regime because it has a smaller hydraulic diameter when compared to the drill pipe area. If the fluid can flush the cuttings out from a larger annular diameter between drill pipe and hole size, it will certainly flush out the cuttings from annular region between BHA and the open hole.

The variables which impact the cuttings removal efficiency are:

- Cuttings size
- Cuttings density
- Density difference between drilling fluid and cuttings
- Effective annular velocity, which is the difference between annular velocity and cuttings' slip velocity
- Carrying capacity of the fluid, represented by the shear stress value at 300 RPM

The other variables (hydraulic diameter, etc.) which affect the cuttings removal efficiency, are already included in the shear stress calculation of the fluid at 300 RPM.

Like the shear stress formula, here also the variables were subjected to their judicial representation in accordance to their effectivity in cuttings removal and, every chosen parameter was offered adequate treatment to eventually have its inclusion to the extent necessary.

The formula was devised with the help of numerical analysis and incorporating the impact of each variable in a manner that speaks about the impact with respect to each other in dynamic way to obtain the real-time data. Here also, there are variables over which there is no control but they are capable of influencing the cuttings removal efficiency. They are:

- Shape of the cuttings
- Duration of no circulation
- Lithology of the rock to alter the shear stress by partly dissolving in drilling fluid due to swelling of its reactive clay
- Pumping of hi-vis sweeps
- Idle circulation (circulation without drilling)
- Pipe rotation
- Pipe eccentricity
- Friction factor

The literature is full of work caried out on the same topic, but the present work is entirely different as it is linked with the real time shear stress calculated value, based upon the multi-variate linear regression analysis without the use of rheometer data as rotational viscometer data invariably suffer from several short-comings, already mentioned in the paper and the attempt here is to be as close to bottomhole conditions as realistically possible. This is (to the author's knowledge), the first such attempt made by amalgamating the shear stress at actual bottomhole conditions and that precisely makes this work different from all such work carried out so far.

Computer-assisted simulations provided the necessary correction factor/s for these uncontrollable variables which reflected in the form of calculated and controlled alteration in numerical values of controllable variables to include the correction factor and improve the accuracy of the final formula. While arriving at a formula, it was realized that there cannot be a single formula for vertical and directional hole because of the drastic variation in the trajectory that makes cuttings removal a tough challenge. Thus, two sets of data and formula were finalized, one each for vertical and directional hole. The numerical values of angle in the hole are larger than their impact in hindering the cuttings removal process. Thus, the hole angle values were given an appropriate numerical treatment to get their value inclusion in formula, close to 1.0 for angles 15 ±3 degrees and the section of the hole with an angle below 12 degree is to be treated as vertical.

A brief description of the steps of software formation process is depicted as:

- Tkinter and Graphical user interface were the tools chosen
- A full window was created with the help of main loop
- Mathematical module was then installed to perform various calculations
- Now the software is ready to perform calculations, once the user inputs the required data

The validity of the process was evidenced by the fact that the computer simulation and the final values of cuttings removal index obtained were in line with the trends observed in industry.

Cuttings Removal vs Hole Cleaning

It is important here to clarify that the formula shall predict cuttings removal efficiency and NOT the hole cleaning efficiency. A hole can partly collapse due to various reasons and cuttings can fall in it during stagnant stages of drilling, which gets reflected in the form of fill/obstruction during tripping in / out. Therefore, if the hole has cuttings left in it despite the formula showing satisfactory removal of cuttings, it need not be necessarily evidence of the error in the formula. In order to ensure that the hole remains cuttings-free during stagnant conditions also, the drilling fluid must have adequate shale inhibition and the right drilling fluid weight as well as extremely low API fluid loss to prevent the hole from destabilizing.

The correction factor to mitigate the error in the formula due to adverse/favourable impact of intangible factors is inherent and the final result appears in the form of "Cuttings Removal Index" (CRI). The values of the CRI have been categorized as below:

- If the formula calculates the CRI > 40, then the efficiency of cuttings removal is "very good".

Cuttings Removal Index in Vertical Holes:

$$CRI = \frac{300\ RPM\ Shear\ Stress * Effective\ Annual\ Velocity * Mud\ Wt}{ROP * Cuttings\ Size * Density\ Difference\ Between\ Cuttings\ and\ Mud} \tag{Eq. 5}$$

$$Effective\ Annular\ Velocity = Annular\ Velocity - Cuttings\ Slip\ Velocity \tag{Eq. 6}$$

Cuttings Removal Index in Directional Holes:

$$CRI = \frac{300\ RPM\ Shear\ Stress * Effective\ Annual\ Velocity * Mud\ Wt}{ROP * Cuttings\ Size * Density\ Difference\ Between\ Cuttings\ and\ Mud * \ Regressed\ Hole\ Angle} \tag{Eq. 7}$$

- If the formula calculates the CRI < 40, but > 20, then the efficiency of cuttings removal is “Average”.
- A CRI of 20 or below indicates “poor” cuttings removal.

There are several ways in which the CRI can be improved but the right way shall depend upon then existing conditions during actual drilling and it is the discretion of the user to choose the way, as deemed fit. The software refrains from any recommendations, as the chosen recommendation has to come from the real-time observations of the operational team. Yet, it hints at possible options to improve cuttings removal efficiency.

Good/standard drilling practices are always handy. The factor often forgotten / neglected is the ROP.

Everyone tries to drill fast but “How fast?” is a matter of debate! The ultimate goal should be to drill at that rate which does not lead to accumulation of cuttings after adhering to most suitable values for the variables and keep the hole free of cuttings. Often the hole cautions us, but we tend to miss the signals. The generic formula to calculate CRI in vertical holes is given in Equation 5 and Equation 6. The generic formula for calculating CRI in directional holes is given in Equation 7.

Knnamponity

For the first time in the industry, it is being hypothesized that non-aqueous fluid, at high BHCT with higher OWR will behave very close to Newtonian fluid at very low shear rates with low solids content in the mud. As shear rate increases, temperature decreases, solids content increases, or OWR decreases, the extent of the Newtonian character of the fluid keeps diminishing. In short, one can say that transition of Newtonian to Non-Newtonian character happens gradually; a quasi-transition state exists between these two states, defined as “Knnampion state”. A Newtonian fluid will first turn “Knnampion”, and then Non-Newtonian with a decrease in OWR, BHCT, and an increase in shear rate. An empirical number is being derived that can characterize the range of value of “Knnamponity”, when the fluid changes from Newtonian to non-Newtonian

Conclusions

The work carried out has the potential to find application in real drilling scenario and the calculations have been carefully crafted to obtain the results that are more relevant to operations on a daily basis. Frequent use of data is required in order to familiarize and extract meaningful information which can then be used for minimizing the NPT by improving hole cleaning efficiency of the system.

The difference in density of mud and cuttings has a role to play in cuttings removal. The less the difference, the better will be the cuttings removal. However, decreasing the density difference by raising the mud weight to improve cuttings removal is not recommended as mud weight is linked with other important aspects of drilling efficiency and safety.

Instead of annular velocity, the current popular norm of evaluating the cuttings removal efficiency, it is in fact the effective annular velocity which plays a major role in cuttings removal efficiency. Decreasing the cuttings slip velocity by making suitable modifications in mud properties, wherever feasible without adversely affecting any important other role of drilling fluid, can be a viable option to improve cuttings removal efficiency.

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Nomenclature

AIML = Artificial intelligence machine learning
API = American Petroleum Institute
BHCT = Bottom hole circulating temperature
BHA = Bottomhole assembly
CRI = Cuttings removal Index
K = Consistency Index
HTHP = High temperature high pressure
IIPE = Indian Institute of Petroleum and Energy
Mud wt = Mud weight
N = Flow behaviour index
NPT = Non-productive time
OBM = Oil-based drilling fluid
OOR = Out of range
PDEU = Pandit Deendayal Energy University

ROP = *Rate of penetration*
RMSE = *Root mean square error*
RPM = *Revolutions per minute*
WBM = *Water-based drilling fluid*

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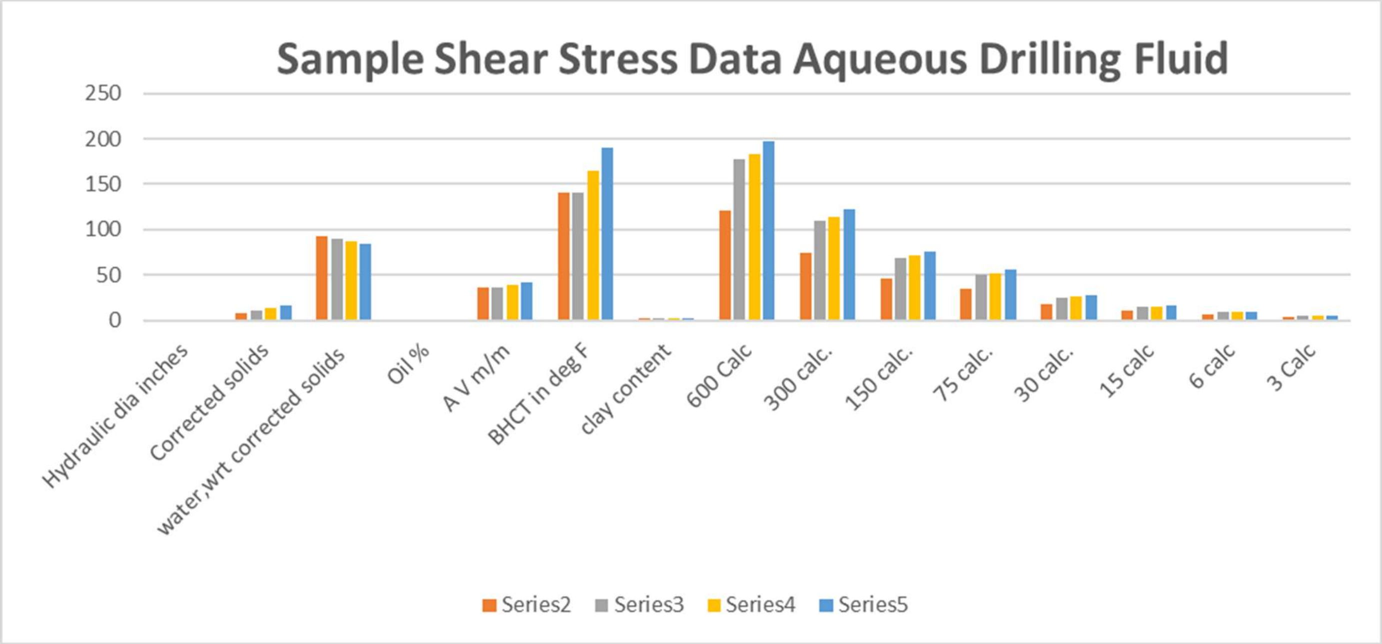

Figure 1: Shear stress data for aqueous drilling fluid.

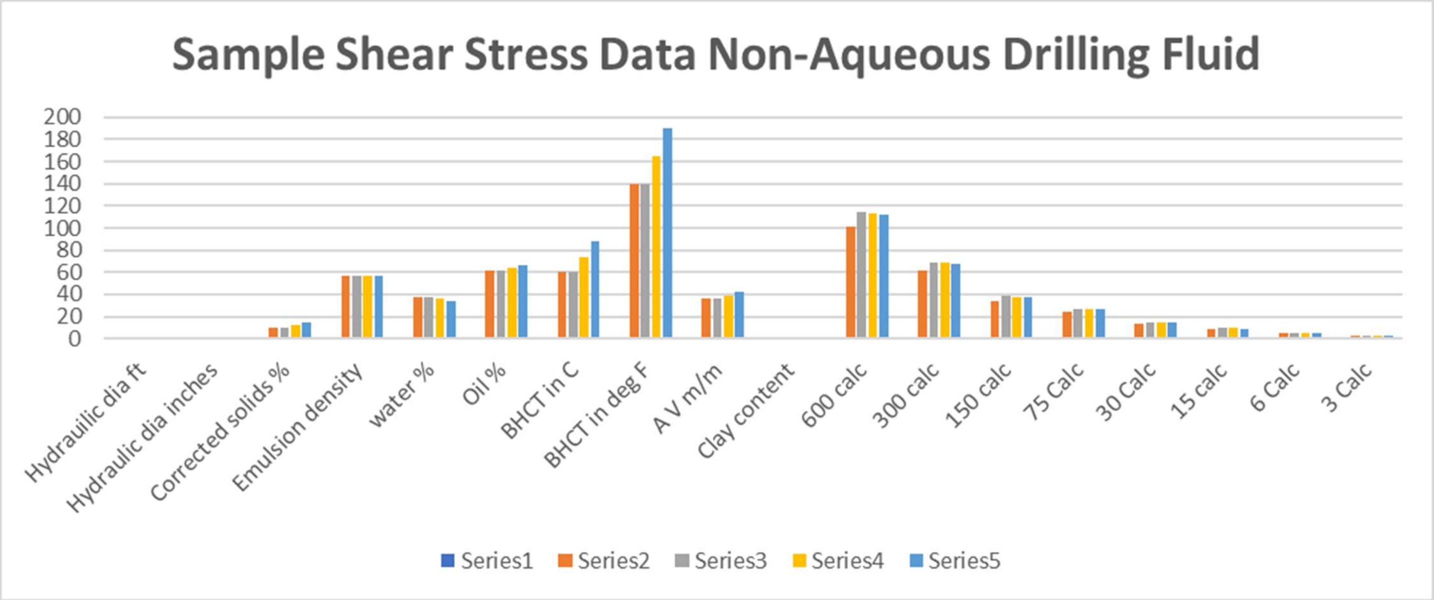

Figure 2: Shear stress data for non-aqueous drilling fluid.

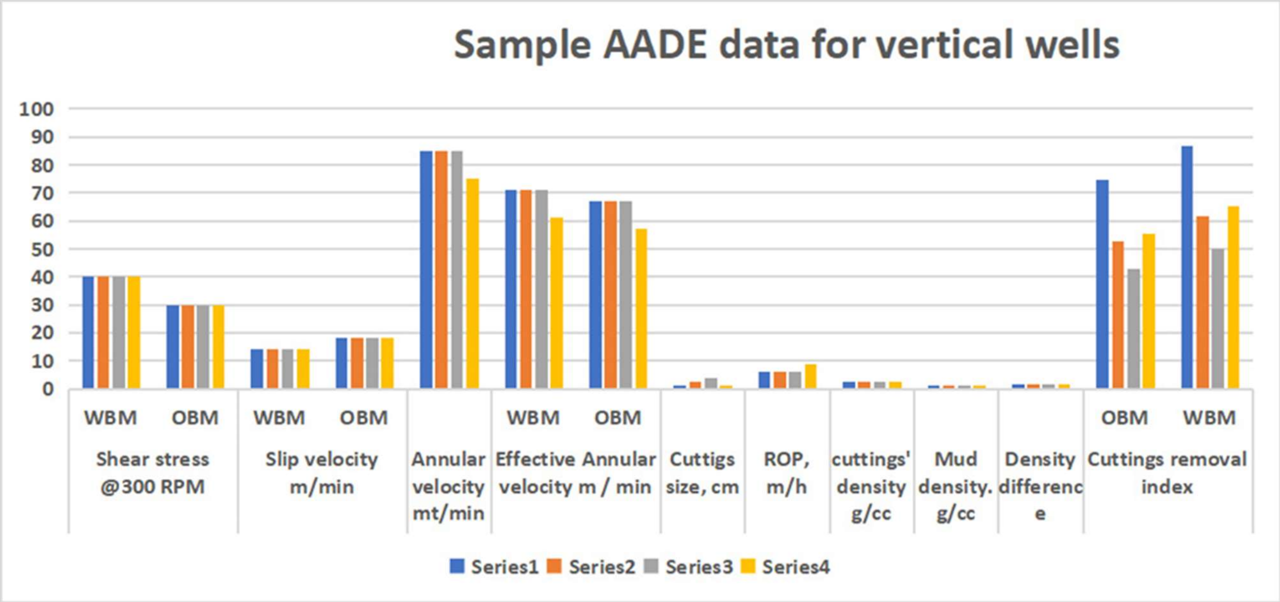

Figure 3: Sample data for vertical wells.

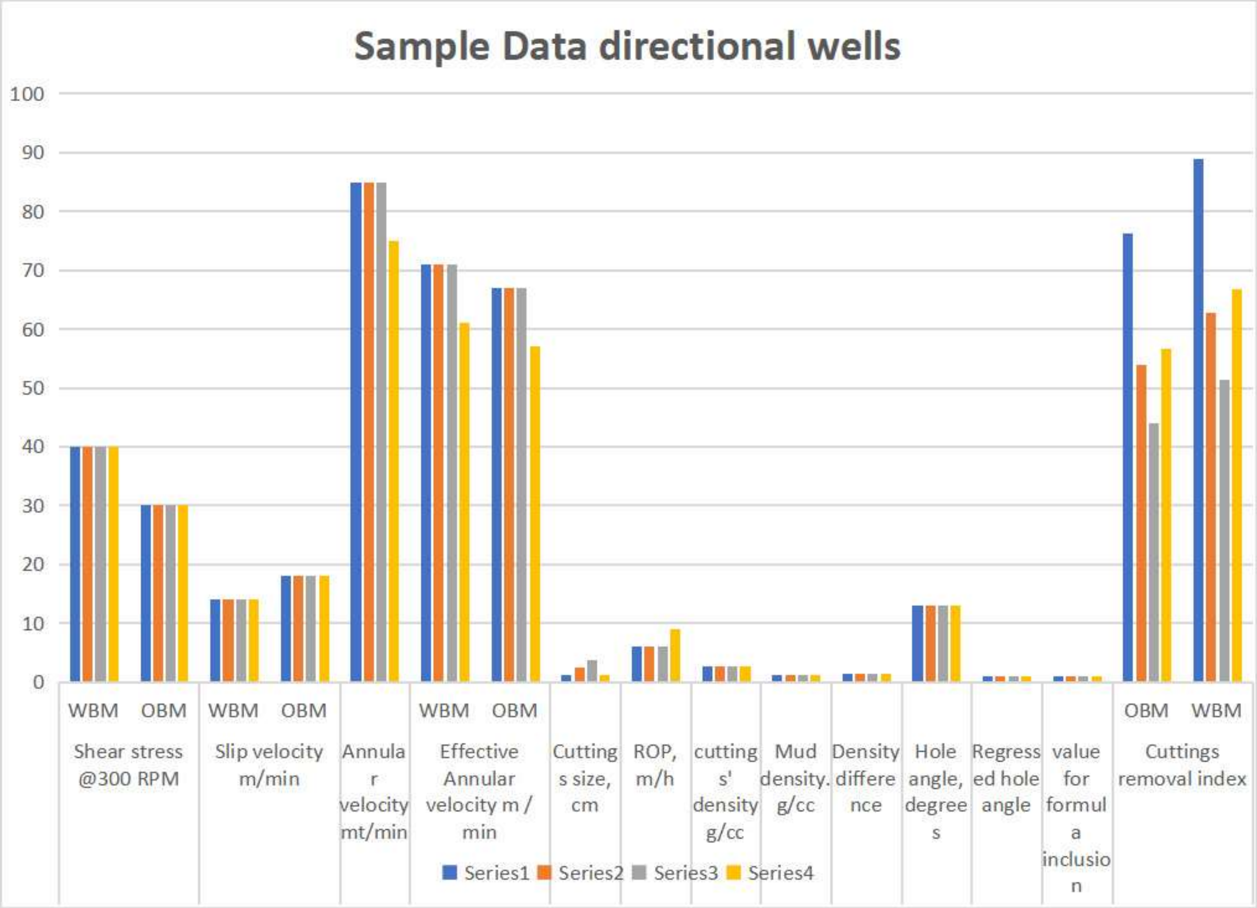

Figure 4: Sample data for directional wells.