Article

Not peer-reviewed version

A Novel Model for Real-Time Evaluation of Hole Cleaning Conditions with Case Studies

Mohammed Al-Rubaii , Mohammed Al-Shargabi , Dhafer Al-Shehri *

Posted Date: 23 April 2023

doi: 10.20944/preprints202304.0779.v1

Keywords: real time evaluation; deviated wells; hole cleaning index (HCI); case studies; drilling performance improvement

Article

A Novel Model for Real-Time Evaluation of Hole Cleaning Conditions with Case Studies

Mohammed M Al-Rubaii [1], Mohammed Al-Shargabi [2] and Dhafer Al-Shehri [1,*]

[1] Department of Petroleum Engineering, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia.
[2] School of Earth Sciences & Engineering, Tomsk Polytechnic University, Lenin Avenue, Tomsk, Russia.
* Correspondence: Dhafer Al Shehri (alshehrida@kfupm.edu.sa)

Abstract: When drilling oil and gas wells, hole cleaning efficiency is crucial, particularly in the curved or severely deviated sections. Although many hole-cleaning procedures and models have been developed, most of them have substantial limitations or are difficult to apply in real time. This study aimed to develop a model for the hole cleaning index (*HCI*) that could be integrated into the drilling operations to provide an automated and real-time evaluation of deviated drilling hole cleaning. The new model herein was developed based on the mechanical drilling parameters, enhanced estimated drilling fluid properties, and cuttings characteristics. This *HCI* model was validated and tested in the field, as it was applied when drilling 12.25"-intermediate directional sections in two wells with a total length of approximately 2000 ft each. The integration of the *HCI* helped to attain a much better well drilling performance (50% enhancement) and mitigation of potential problems like pipe sticking and the slower rate of penetration. Since the developed index incorporates the changes in wellbore geometry and other spontaneous field data, the new model could be utilized for real-time optimization and intermediate interventions by drilling teams, unlike commercial software tools which are only useful during the planning phase. For this reason, the *HCI* can be linked to the driller's control panel to provide timely evaluation and corrective measures related to hole cleaning.

Keywords: real time evaluation; deviated wells; hole cleaning index (*HCI*); case studies; drilling performance improvement

1. INTRODUCTION

Drilling vertical and more directional wells in oil and gas industry are very necessary and demanded for global resources of life. Drilling troubles are always there and most of these drilling problems are stuck pipe incidents due to improper hole cleaning, lost circulation and well control incidents. Optimization of downhole cleaning during drilling can be achieved either by improving engineering aspects or enhancing chemical efficiency and most of the time by applying both appropriately. In planning and designing of drilling wells, drilling time and flat time must be suitably optimized to obtain the best drilling efficiency and cost effectiveness.

Hole cleaning during drilling plays a significant role in reducing drilling time by ensuring an enhanced rate of penetration (ROP) and a flat time by minimizing tripping operations, pumping sweep pills, time of circulation, time spent on running of casing, and improving cementation integrity and efficiency. Improper hole cleaning cause drilling problems such as high or erratic trends of equivalent circulating density, torque and drilling drag, wellbore instability, high annulus pressure, lost circulation, areas of tight hole sections encountered during tripping, and stuck pipe and well control incidents. Hole cleaning is an effective tool used to overcome wellbore instability during drilling in case cutting accumulation and shale sloughing and caving are encountered. Cutting accumulation and caving will lead to difficult tripping operations resulting from pipe sticking as reported by (Fjaer et al., 2008).

33% of stuck pipe incidents are due to insufficiency of down-hole cleaning while drilling and is responsible for a large portion of all stuck pipe events (Mitchell, J 2011). Hole cleaning efficiency can be affected by mechanical and chemical influences or a combination of both. Mechanical effects are normally due to the density of mud (too high or too low) and drilling mud parameters or the use of inappropriate drilling practices (such as the penetration rate, influence of vibration, torque, and drag and not performing wiper trips when drilled hole section demands). On the other hand, chemical effects are due to the use of drilling fluids with improper rheological properties and improper concentrations of inhibitors or chemical additives added to manage the anticipated rheology adjustments. Non-Newtonian fluids are more efficient than Newtonian fluids owing to rheological parameters of drilling fluids affecting their lifting capacity and contributing to optimize the carrying capacity and transportation ability, efficiency, and energy of drilling fluids. Most models of drilling fluids, including Bingham plastic, power law, and Herschel-Bulkley, are based on non-Newtonian behavior of fluids. Generally, a main reason of lost directional drilling wells which might not be accomplished to reach their objective was poor hole cleaning due to drill cuttings accumulation in the hole next to the lower part of parted drill string or drill pipe (Laik, 2018). As indicated in Table 1, several logical reasons explain why exceeding the limit of cutting accumulations can induce hole problems.

Table 1. Problems caused by the concentration of cuttings in the annulus and their impact.

Problems	Impact
Increased PV, YP, Gels, and 6 and 3 RPM viscometer readings	• Poor cutting transport. • High ECDs and possible break down of formation and lost circulation
Increased fluids loss/thick filter cake	• Differential sticking and high torque and drag
Slow ROP	• Chip hold down pressure
Increase in density	• Possible breakdown of the formation • Increase dilution and addition of chemicals to maintain proper density
Poor cement displacement	• Channels that allow pressure communication up the wellbore.
Increased abrasion and wear of mud pumps and down hole motors and tools	• Increased cost and lost time
Increase disposal cost of drilling waste	• Environmental and health safety

The preferred drilling fluid regime while drilling, i.e., laminar, transition, or turbulent, depends on the type of drilled hole section including whether vertical or directional. In vertical drilling, the preferred fluid flow regime is laminar, which provides an efficient bouncy effect and a maximum annular velocity profile at the walls of the drilled hole section to ensure a proper lifting capacity. In deviated, highly deviated, or horizontal hole sections, a turbulent flow regime is required to dislodge and mobilize accumulated cuttings on the lower side of the hole section and underside of the drill string. Finally, the drilling fluid is selected based on the lithology of the drilled formation, which is an uncontrollable factor taken into consideration during the planning phase of the well design. In the field, mud solid control equipment, such as shale shakers, degassers, desanders, desilters, mud cleaners, and centrifuge devices must be taken into consideration to ensure proper hole cleaning. Mud solid control efficiency and its correct loop contribute to practical hole cleaning to ensure efficient performance of mud solid control equipment, faster ROP, maintenance of proper mud rheological properties, and control of the additional amount of dilution and mud chemical additives in drilling fluids.

A knowledge of the chemistry of drilling mud is important to understand the performance of chemical hole cleaning. Chemical influences and the effects of reactions on the lifting capacity of the drilling fluid can ensure proper downhole cleaning if they are appropriately manipulated and are compatible with the WBM or OBM used. As mud chemical materials are extensively used in drilling, understanding chemical factors is essential to maintain optimal drilling efficiency. Knowledge of basic chemistry is important to optimize chemical hole cleaning and address drilling problems safely and in an environmentally friendly manner.

Chemical additives are also used to optimize drilling efficiency, minimize wellbore instability, and assist tripping drilling operations. Rheology of drilling fluids can minimize drilling problems, including drill bit balling, drilling tight spots during tripping drilling operations, drill bit wear, and problems encountered in other drilling applications. Chemical additives can be viscosifiers, friction reducers, weighting agents, fluid loss agents, hole and mud conditioners, deformers, inhibitors, rheology modifiers, and deflocculating agents. Physical and chemical properties that contribute to efficient transport of cuttings are yield point, apparent viscosity, average annular mud velocity, cuttings slip velocity, and gel strength.

The density of the drilling fluid is extremely important to balance the drilled hole section to prevent formation fluid flowing and to maintain wellbore stability mechanically in the case of shale caving or sloughing. Also, introducing chemical additives such as shale inhibitors can maintain reactive shale formation, while other chemicals can enhance ROP, increase mud efficiency, reduce drill bit wear, avoid bit and bottom hole assembly (BHA) balling, and condition the hole section and drilling mud. Annular velocity cools the drill bit and density, and annular velocity transmits hydraulic horsepower to the drill bit using the appropriate viscosity and proper sizes of bit nozzles. Hole cleaning is an important factor to consider to avoid drilling troubles because if hole cleaning was not performed effectively and applicably, that could lead for well lost. Hole cleaning studies in vertical and directional wells were performed during the 1970's and in the early 1980's. The function and mechanisms of drilling mud to carry and hold up the generated drilling cuttings while drilling operation in dynamic and static conditions is defined as hole cleaning efficiency (Hossain &Islam, 2018).

Performing an effective hole cleaning performance while drilling will help to achieve time and cost effectiveness during drilling operations (Terab et al, 2016). Cuttings accumulation or debris can continue to remain in the drilled hole section and that will make drilling operation difficult to be executed during drilling (Ferreira, 2012). Efficient hole cleaning and removal of cuttings are challenges in designing and drilling vertical and directional hole sections of wells. There three important criteria must be considered to achieve hole cleaning optimization such proper well planning, rheological properties of drilling mud, and following best practices of drilling. The effectiveness of removal of cuttings is influenced by several factors, including the dimensions of drill cuttings, optimization of bit hydraulics, hole angle, drill string rotation, and drill pipe eccentricity (Moore, 1986; Okrajni and Azar, 1986; Guo et al., 2011; Ramsey, 2019).

Improper down hole cleaning can make fill or accumulation of drill cuttings above drill bit for that reason, sufficient capability of drilling mud pump is required to provide optimum flow rate and smooth pressure that can supply effective down hole cleaning, adequate average mud annular velocity for lifting generated drill cuttings, and robust hydraulic horsepower to generate motion for down hole motors with providing designated pressure drop throughout selected drilling bit jetting nozzles (Finger & Blankenship, 2012). Many hole cleaning indicators and drilling practices using charts have been developed. However, these models are based on a limited number of parameters affecting the status of hole cleaning. Hole cleaning during drilling is a key task, especially for directional wells. This is because poor hole cleaning can cause many problems, including stuck drill string, hole collapse, high equivalent circulating density *(ECD)*, wall fracture of the hole section, and high loading of drill cuttings in the annulus. Effectiveness of down hole cleaning can be ensured by incorporating prime mud rheological parameters and superior drilling monitoring methodologies. The ability of drilling mud (drilling fluid) to effectively remove the drill cuttings from drilled hole sections and produce very clean holes depend on many factors, including the weight of the drill cuttings and mud, diameter and inclination of the hole section, rheological mud parameters, size of the cuttings, use of hole-cleaning pills, *ROP*, eccentricity of the drill string, drill string rotation, multiphase flow effect, transport ratio of the cuttings, and the properties of the cutting bed. Many experimental and theoretical studies have been performed to understand parameters that affect the hole cleaning performance.

Hole cleaning is a fundamental function of mud, and this function is also the most used and misunderstood. Cleaning of deviated holes is most challenging because of changing formation lithologies and the drill cuttings. In addition, when the cutting beds (cuttings accumulation height) are at a hole inclination between 35-50 degrees, the drill cuttings are more likely to slide downwards negatively affecting the hole cleaning (Tomren et al. 1986; Peden et al. 1990; Sifferman and Becker 1992).

Even though increasing the mud flow rate can reduce the height of the bed of drill cuttings, it will not be very effective in directional wells (Tomren et al., 1986; Li and Walker, 1999; Hyun et al., 2001). Pigott (1935) recommended that the concentration of the cuttings in the annulus must remain less than 5% to prevent pipe stuck problems. Newitt et al, (1961) found a precise equation for drilling cuttings volumetric concentration in annulus for steady state lifting of drill cuttings in vertical tube. Mitchell, B (1992) developed equation for quantifying average cuttings concentration in annulus while drilling and after stopping circulation while making connection.

Al-Azani et al, (2019) predicted real time cuttings concentration in annulus by using *(ANN)* including *(BPNN)* Back-propagation neural network & *(RBFN)* Radial basis functional network and *(SVM)* which are classified as artificial intelligent tools. The selected parameters were *MW, PV, YP* temperature, *GPM, RPM, ROP*, pipe eccentricity and inclination of hole section. The results were validated with 116 experimental studies in literature review domain. The accuracy was 0.9 R and average absolute error (AAE) less than 5%. Al-Rubaii et al, (2020) developed a new real time model for cuttings concentration in annulus by the influence of GPM & ROP and the model was applied on real time data and validated with Newtis and API models.

The model showed acceptable accuracy and the results. Experimental investigations performed by Hussaini & Azar (1983) and Azar (1990) indicate that mud rheology also affects hole cleaning. The results of thses investigations confirmed that the carrying efficiency of drilling mud increases when the percentage of the ratio between the mud yield point *(YP)* and the mud plastic viscosity *(PV)* is maximized.

Determining the density and size of drill cuttings during drilling to estimate the slipping velocity of drill cuttings is critical and vital. Additionally, when the viscosity of drilling mud is high, the effectiveness of mud in cleaning the hole by removing the drilled cuttings will also be high. Pipe rotation significantly improves the efficiency of hole cleaning if the drill string has a high eccentricity for both vertical wells (Ravi and Hemphill, 2006) and inclined hole sections according to (Sanchez et al., 1999).

Ogunrinde and Dosunmu (2012) have developed a model to estimate the optimum rate of penetration *(ROP)* and mud pump flow rate *(GPM)* to be used during drilling to maintain proper hole cleaning. R. S. E. R (2013) developed a modified model to predict drilling string vibration during drilling to prevent damage or twisting-off of the bottom hole assembly *(BHA)* and associated poor hole cleaning. Al-Rubaii et al., (2018 & 2020) have developed new methodology for hole cleaning by improving *ROP* through evaluation and adjustment of the carrying capacity index and accumulation of drill cuttings in the annulus of the drilled hole section simultaneously to improve drilling performance by more than 20%.

In addition to that they did modification for *(CCI)* by including cutting rise velocity with annular velocity and then applied *CCI* on real time data to monitor and evaluate the hole cleaning efficiency to optimize well and rig performance. Alawami et al., (2020) applied the hole cleaning carrying capacity index *(CCI)* in real time data to monitor and evaluate the hole cleaning performance of drilled well by using offline real time data. Mahmoud et al., (2020) modified the cutting capacity index *(CCI)* to make it applicable in cleaning deviated hole sections. They modified the original carrying capacity index taking the effect of inclination on the annular velocity and equivalent circulating density into consideration. saihati et al., (2021) developed a predictive drilling torque model using machine learning techniques to monitor downhole conditions, such as poor hole cleaning conditions. Huaizhong et al., (2019) did an experimental and a numerical simulation study for cuttings transport in narrow annulus to maximize rate of penetrations of coiled tubing that is partially underbalanced to solve the problem of wellbore instability. The outcome of measurements is particle velocity, particle distribution, phenomenon of collision of particles and sinking and rising

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 April 2023 doi:10.20944/preprints202304.0779.v1

of particles. The obtained results were that the particle velocity declines with the increase of rotational speed and increases with the increase of flow rate.

Ytrehus et al., (2019 & 2021) used micronized barite that was used for providing lower viscosity drilling fluid, non-laminar flow, which is advantageous for particle transport in near-horizontal sections. They found that low-viscous fluids are more efficient than viscous fluids at higher flow rates and low drill string rotation. Different fields applied oil-based drilling fluids with similar weight and varying viscosities and positive noticeable results showed cuttings transport performance, hole cleaning abilities and hydraulic frictional pressure drop.

Pedrosa er al., (2022) investigated the influence of rheological properties of three different types of fluids on the erodibility of the cuttings-bed. Three outcomes were measured such as erodibility of the cuttings bed, shear rates of different types of fluids, flow rates dependency along the dune extent. The results showed that the cuttings-bed is eroded by dune movement.

Shirangi et al., (2022) developed a new digital twin methodology for predicting drilling fluid properties to perform real-time calculations for hole cleaning by combining several models using the large amount of offset data integrated in the model. Tables 2 and 3 shows a summary of major findings for other studies related to hole cleaning chemistry and engineering.

Table 2. Major Findings (hole cleaning Chemistry).

Year	Author	Technique	output
1906	Einstein	Rheology	Effective viscosity by including the influence of the concentration of solid particle
1992	Frenkel, et al.	wellbore-instability	kaolinite is the most dispersive followed by illite, while smectite is not highly dispersive
1997	Zhou, Z	clay swelling mechanisms	the expansion of clay is due to the increase in spacing between the clay layers
1998	McCollum	Rheology	low mud rheology, reduction in the accumulation of cuttings and controlling solids in mud
2009	Stephens et al.	swelling tests	high swelling percentage is a clear indicator of low efficiency of drilling fluid inhibition against swelling
2010	Zoback	wellbore-instability	Swelling of shale is due to the increase in vapor pressure within shale leading to weakening of adherence and development of washout
2010	Abedian and Kachanov	Rheology	effective viscosity of a Newtonian fluid with rigid spherical particles
2016	Aberoumand et al.	Rheology	nano-fluid OBM viscosity
2018	Deng	Rheology	higher bentonite concentration and a lower biopolymer concentration normally showed better hole cleaning capacity
2019	Vanessa Boyou et al.	Rheology	nanosilica WBM improves the tarnsport efficiency of cuttings
2020	Ofei et al.	Rheology	increasing mud density, hole cleaning efficiency can be increased
2020	Sargani et al.	Rheology	CCI showed a high value at a 60/40 oil-water ratio
2020	Alsaba et al.	Rheology	MgO showed the highest improvement in hole cleaning, while TiO2 resulted in the lowest improvement

Table 3. Major Findings (Engineering).

Year	Author	Technique	Output
1985	O'brien	Factors	A higher yield point value is required with larger cuttings
1991	Becker And Azar	Factors	Impact of inclinations on cutting bed and cuttings concentration
1992	Luo et al.	Rheology & Factors	The rheology factor and the corrected minimum required flow rate with the used ROP and induced washout during drilling.
1994	M. R.-I. D	Indicators	Cuttings bed height and hole cleaning ratio (HCR)
1995	Beck	Rheology	Qualitative relationships between the rate of penetration and the rheological properties of the drilling fluid (PV, n, Reynold number)

doi:10.20944/preprints202304.0779.v1

2000	Adari et al.	Factors	Ranked the hole cleaning factors in drilling and the time to effectively clean the wellbore
2006	Berg et al.	Modeling	Flow chart for ensuring effective displacements for wellbore cleanness of open hole and cased hole prior of running completion
2007	Shariff et al.	Factors	Eccentricity & cuttings concentration
2009	Saasen et al.	Factors	Drill string rotation in a deviated hole with an appropriate flow rate can remove the bed of cuttings and an optimal hole cleaning can be achieved
2011	Malekzadeh and Salehi	Modeling	The optimum flow rate ensuring both good hole cleaning and drilling hydraulics in a directional well to achieve an optimized ROP
2019	Alkinani & Al-Hameedi.	Rheology	ECD increases with PV and solid content, while it decreases slightly or is mostly stable with increasing values of YP
2021	Ahmed, A et al.	Modeling	The important parameter for hole cleaning with an engineering methodology to consider the hole enlargement
2022	Jimmy et al.	Modeling	A new cutting lifting factor

All current hole cleaning models and commercial software are used only for planning purposes and do not contribute to the optimization or intermediate interventions by drilling teams. Most of these models do not validate their approach based on real-time field data and past data for drilled wells.

The main objective of this study is to introduce a newly developed hole cleaning index (*HCI*) to achieve effective downhole cleaning by applying the required adjustment to optimize the drilling process. This method implements automated carrying capacity indicator modifications. The developed *HCI* enables real-time monitoring and evaluation of the status of hole cleaning during drilling.

2. DEVELOPMENT OF A NOVEL HOLE CLEANING INDEX

The novel real-time indicator of the status of hole cleaning developed in this study is based on the carrying capacity indicator of the cuttings developed by (Robinson and Morgan, 2004). The new indicator considers all the important factors affecting the status of hole cleaning and is called the hole cleaning index (*HCI*). *HCI* was developed starting from the *CCI* calculated using [Eq. 1. Where k is the consistency index as defined by Eq. 2, AV is the average annular velocity, and MW is the drilling fluid density in (lb/ft3).

Where n is the flow behavior index defined by the consistency index (k) with a low shear yield point (LSYP) as defined by Eq. 3 and Eq. 4. Generally, the consistency index, k, describes the thickness of the fluid and is thus somewhat analogous to apparent viscosity. As the consistency index, increases, the mud becomes thicker (Whittaker, 1985). The flow behavior index, n, determines whether the fluid becomes less or more viscous as the shear rate increases (Lavrov, 2016). The original expressions for k and n do not contain LSYP. Here, the expressions for k and n of the developed real-time model take LSYP into account, and the LSYP term is a function of the viscometer readings at 3 and 6 rpm. Where PV denotes the plastic viscosity of the drilling fluid (cp), YP is the yield point of the drilling fluid (lb/100 ft2).

The plastic viscosity (PV) represents the mechanical friction between drilling fluid solid and fluid that cause resistance to flow (Hossain & Al-Majed 2015). The yield point (YP) is the minimum value of stress that is required to move the fluid (Elkatatny et al, 2018). R3 is the viscometer reading at 3 rpm and R6 is the viscometer reading at 6 rpm which can be used for seeking to predict the yield point at low share rate that can be defined as low shear yield point (LSYP). Specifically, LSYP can contribute significantly in hole cleaning efficiency and ability of drill cuttings transportation in drilling of directional wells and it is critical and important as YP during drilling wells. In drilling operations practices it si highly recommended to have increased YP and a decreased LSYP (Murtaza et al 2021).

In addition to that, (Bern et al 1996) defined LSYP as the minimum yield stress for preventing solids settling (Sagging). The value of LSYP can be dramatically decreased by increasing the pH, because, the increase of pH readings can support the minimizing of the bentonite's dispersion

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 April 2023 doi:10.20944/preprints202304.0779.v1

particles, and then the particles of bentonite will not assist the fluid viscosity to be established. Hence, the lifting capacity of drilling mud to transport the generated drill cuttings will be minimized (Gamal et al, 2019). The standard API of measuring low share yielding point is defined as (LSYP = 2R3 – R6) which is used to estimate proper yield stress (Zamora et al 2005). For a newly developed hole cleaning index, the LSYP was considered for better simulation of hole conditions and rheological drilling fluid influences while drilling operations.

The flow behavior index, n, can be expressed as a function of PV, YP, and LSYP as defined by Eq. 5, and the subscript m is used to indicate the modified parameter. Substituting Eq. 3 into Eq. 1 and replacing CCI with the new parameter HCI yields Eq. 7.

The average annular velocity (AV) as expressed in Eq. 8 is a drilling hydraulic parameter, which can be modified to include the effect of the hole inclination and the impact of the cutting slip velocity defined by Eq. 9. Modified annulus velocity (AVm), which is equal to Vtransport, is defined by Eq. 9 as the summation of the velocity corrected for the wellbore inclination effect (Vcorrected) and cutting slip velocity (Vslip). where Vcorrected and Vslip are in (ft/min). Vcorrected and Vslip can be defined by Eq. 10 and Eq. 11, respectively.

where Q is the mud pump flow rate (gpm), OH is the hole size (in), OD is the drill pipe outside diameter (in) in the drilling string design, α and β are the inclination and azimuthal directions of the hole (degrees), respectively, ROP is the drilling rate of penetration (ft/h), and DSR is the drill string rotation (revolutions per minute or rpm). By combining equations from Eq. 8 to Eq. 11, the transport velocity or the modified annular velocity can be expressed as indicated in Eq. 12.

Where Vann is expressed as a function of Q, OH, and OD by Eq. 13 which is the original annular mud velocity applied in vertical hole section only. The modified annular velocity as defined in Eq. 12 is a function of the flow rate and weight of the drilling fluid, size of the drilled hole, outer diameter of the drill pipe, rate of penetration, drill string rotation, plastic viscosity, yield point, the viscometer reading at 3 rpm, the viscometer reading at 6 rpm, wellbore inclination, and azimuthal directions. MW in Eq. 7 is replaced by the equivalent mud weight (EMW), which accounts for the weight of the cuttings' influence and is a function of ROP, OH and Q.

An equivalent mud weight (EMW) that incorporates the cuttings accumulation (CA) is presented by equation 14. CA is calculated using Eq. 15. Finally, HCI is expressed as a function of Km, AVm, and EMW, as defined by Eq. 16 with Km, AVm, and EMW calculated using Eq. 4, Eq. 12, and Eq. 14, respectively. As discussed earlier, HCI takes the influence of many parameters, including rheological parameters and density of the drilling fluid, mechanical parameters associated with drilling, well trajectory survey, mud velocities, rate of penetration, drill string rotation, and cutting accumulation load into account to determine the status of hole cleaning.

The application of HCI to determine the status of hole cleaning during drilling is based on the classification of the HCI value. As the HCI parameter developed in this study is based on CCI, the classification ranges for the HCI parameter are based on the ranges of CCI. CCI has two classification ranges of CCI > 1, which indicates proper hole cleaning performance during drilling, and CCI < 1, which indicates insufficient hole cleaning.

Classification of CCI was also adopted for the HCI parameter. An HCI value greater than 1 indicates proper hole cleaning, while a value of HCI less than 1 indicates ineffective hole cleaning, which may lead to induced problems during drilling. Under such circumstances, quick intervention to stop drilling is essential, and the hole and mud must be conditioned while performing circulation and pipe rotation with or without reciprocation.

$$CCI = \frac{k \times AV \times MW}{400000} \quad \text{[Eq. 1]}$$

$$k = \left((PV + YP)\right)(510)^{1-n} \quad \text{[Eq. 2]}$$

$$k_m = \left((PV + YP) - (\ LSYP)\right)(510)^{-n} \quad \text{[Eq. 3]}$$

$$k_m = ((PV + YP) - (\ 2R3 - R6))(510)^{-n_m} \quad \text{[Eq. 4]}$$

$$n = 3.32\, log\left(\frac{(2PV + YP)}{(PV + YP)}\right) \quad \text{[Eq. 5]}$$

$$n_m = 3.32\, log\left(\frac{(2PV + YP) - (2R3 - R6)}{(PV + YP) - (2R3 - R6)}\right) \quad \text{[Eq. 6]}$$

$$HCI = \frac{((PV + YP) - (\ 2R3 - R6))(510)^{-\left[3.322\, log\left(\frac{(2PV+YP)-(2R3-R6)}{(PV+YP)-(2R3-R6)}\right)\right]} \times AV \times MW}{5867} \quad \text{[Eq. 7]}$$

$$AV = AV_m = V_{transport} \quad \text{[Eq. 8]}$$

$$V_{transport} = V_{corrected} + V_{slip} \quad \text{[Eq. 9]}$$

$$V_{corrected} = \frac{24.5(Q)}{OH^2 - OD^2}\, cos(\alpha) + \left(\frac{60}{\left(1-\left(\frac{OD}{OH}\right)^2\right) * \left(0.64 + \frac{18.2}{ROP}\right)} + \frac{ROP\ (OH^2)}{60(OH^2 - OD^2)}\right) sin\ (\beta) \quad \text{[Eq. 10]}$$

$$V_{slip} = \left(\frac{175\left(0.2\ \left(\frac{ROP}{DSR}\right)\right)\left(22 - \frac{MW}{7.481}\right)^{2n_m}}{(MW/7.481\ )^{0.333}\left(\frac{2.4V_{ann}}{OH - OD}\left(\frac{2n_m + 1}{3n_m}\right)^{nm} \left(\frac{200K_m(OH - OD)}{V_{ann}}\right)\right)^{n_m}}\right) \quad \text{[Eq. 11]}$$

$$AV_m = V_{transport} = \left(\frac{24.5(Q)}{OH^2 - OD^2}\, cos(\alpha) + \left(\frac{60}{\left(1 - \left(\frac{OD}{OH}\right)^2\right) * \left(0.64 + \frac{18.2}{ROP}\right)} + \frac{ROP\ (OH^2)}{60(OH^2 - OD^2)}\right) sin(\beta)\right) + \frac{175\left(0.2\ \left(\frac{ROP}{DSR}\right)\right)\left(22 - \frac{MW}{7.481}\right)^{2n_m}}{(MW/7.481)^{0.333}\left(\frac{2.4V_{ann}}{OH - OD}\left(\frac{2n_m + 1}{3n_m}\right)^{n_m} \left(\frac{200K_m(OH - OD)}{V_{ann}}\right)\right)^{n_m}} \quad \text{[Eq. 12]}$$

$$V_{ann} = \frac{24.5(Q)}{OH^2 - OD^2} \quad \text{[Eq. 13]}$$

$$EMW = MW\ (CA) + MW \quad \text{[Eq. 14]}$$

$$CA = \frac{0.00136\ ROP(OH)^2}{Q} \quad \text{[Eq. 15]}$$

$$HCI = \frac{K_m\ [AV_m]\ EMW}{5867} \quad \text{[Eq. 16]}$$

3. FIELD APPLICATIONS USING THE NEW HOLE CLEANING INDEX

Validation of the new *HCI* was demonstrated while directionally drilling 12.25″ intermediate sections of two offshore wells (Well-A and Wells-B). The two sections were highly deviated sections starting at 30 degrees and ending up nearing horizontal or 90 degrees inclination at the top of reservoir. Table 4 summarizes key characteristics of the drilled formations and cuttings produced during drilling of these sections. The two sections were drilled using an oil-based drilling fluid. Table 5 summarizes drilling fluid properties used to drill these sections.

Table 4. Formation and drilling cuttings properties.

Parameter	Value
Formation lithology type	Sandstone, limestone, and shale
Formation temperature	(140 - 155) °F
Formation porosity	0.15 - 0.25
Washout	10 % - 30 %
Density of drill cuttings	(20 - 24) pound per gallon (ppg)
Size of drill cuttings	(0.2 - 0. 375) inches (in.)

Table 5. The drilling fluid characteristics.

Parameter	Characteristic Range
Oil Based drilling mud density	80 lb/ft3
Oil ratio	(0.75 - 0.8)
Water ratio	(0.2 - 0.25)
Electrical stability	(400 - 600) Volts
Low gravity solids	(2.5 - 5) Percent (%)
High gravity solids	(10 - 15) Percent (%)
March funnel viscosity	(65 - 75) Seconds (sec)
Solid content	(15) Percent (%)
Mud solid control equipment efficiency	0.5

Table 6 summarizes the other rheological properties of the drilling fluid, mechanical drilling parameters, hole section directional survey and hydraulic velocities, required for calculation of *HCI* are listed in for Well-A and in Table 7 for Well-B. A Polycrystalline Diamond Cutters (PDC) drilling bit with 6 nozzles of 16/32′′ size, hydraulic horsepower of 2.5 - 3.8, and total bit flow area of 1.17 square inches was employed to drill the sections under study in both wells. The other components of the bottom hole assembly are listed in Table 8.

Table 6. Well-A measured and calculated parameters.

Measured Parameters	Minimum	Maximum	Average
α	30	90	60
β	69	110	90
MW	80	80	80
PV	30	32	31
YP	23	24	24
R3	12	13	13
R6	13	14	14
WOB	10	39	24
DSR	40	177	153
Q	590	1033	958
SPP	900	2730	2411
Calculated Parameters			

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 April 2023 doi:10.20944/preprints202304.0779.v1

LSYP	11	12	12
K_m	0.32	0.36	0.34
n_m	0.76	0.79	0.775
EMW	82	86	84
V_{ann}	120	211	167
$V_{transport}$	182	419	325
V_{slip}	10	30	20
$V_{corrected}$	170	440	300

Table 7. Well-B measured and calculated parameters.

Measured Parameters	Minimum	Maximum	Average
α	30	90	60
β	55	145	100
MW	80	80	80
PV	30	30	30
YP	23	23	23
R3	11	11	11
R6	8	8	8
WOB	22	39	30
DSR	50	190	171
Q	640	688	685
SPP	1500	2730	3000
Calculated Parameters			
LSYP	14	14	14
K_m	0.23	0.23	0.23
n_m	0.82	0.82	0.82
EMW	82	87	85
V_{ann}	130	140	140
$V_{transport}$	109	390	248
V_{slip}	10	35	22.5
$V_{corrected}$	41.2	171	106

Table 8. Bottom Hole Assembly (BHA) used to drill the 12.25''deviated sections.

Number of joints	Component	OD (in)	ID (in)	Weight (lb/ft)	Connection	Length (ft)
1	12.25 PDC drilling bit	12.25	2.78	150	pin 6-5/8 REG	0.89
1	RSS + Motor	8	5.25	135	Box 6-5/8 REG	35.4
1	Bottom sleeve stabilizer	12.125	-	-	Box 6-5/8 REG	35.4
1	Float sub	8	3	147	Box 6-5/8 REG	2.82
1	String stabilizer	8	3	147	Box 6-5/8 REG	7.24
1	Measurements while drilling (MWD)	8	3.25	143	Box 6-5/8 REG	31.0
1	Downhole screen HOS	8	3.25	143	Box 6-5/8 REG	6.20
4	Drill spiral collar	8	3	147	Box 6-5/8 REG	120.2
1	Drilling jar	8.12	2.75	132	Box 6-5/8 REG	21.8
2	Drill spiral collar	8	3	147	Box 6-5/8 REG	89.7
1	Cross-over	8	3	147	Box 4-1/2 REG	2.89
4	Heavy weight drill pipe (HWDP)	5.5	3	49.3	-	120.3
					Total	473.73

3.1. Application of HCI in Well-A

Well-A,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 April 2023 doi:10.20944/preprints202304.0779.v1

The first case study considered in this work involves a well identified as Well-A where *HCI* was employed during drilling for optimimzing hole cleaning. The changes in *HCI* and other drilling parameters of this case are shown in Figure 1. In Well-A, during drilling at a depth of X500 *HCI* value is more than 1.1, indicating that the wellbore is clean without accumulation of any cuttings. The crew also did not observe any other indication for the accumulation of cuttings. At a depth of X760 ft, *HCI* value begins to continuously decrease from 1.17 to less than 1.1 at a depth of X840 ft, as shown in Figure 1. As indicated in this Figure, the decrease in *HCI* is not caused by an increase in ROP. Hence, the crew decided to clean the hole by increasing the pumping rate of drilling fluid from 750 to 915 gpm, which increased *HCI* from less than 1.1 to more than 1.15.

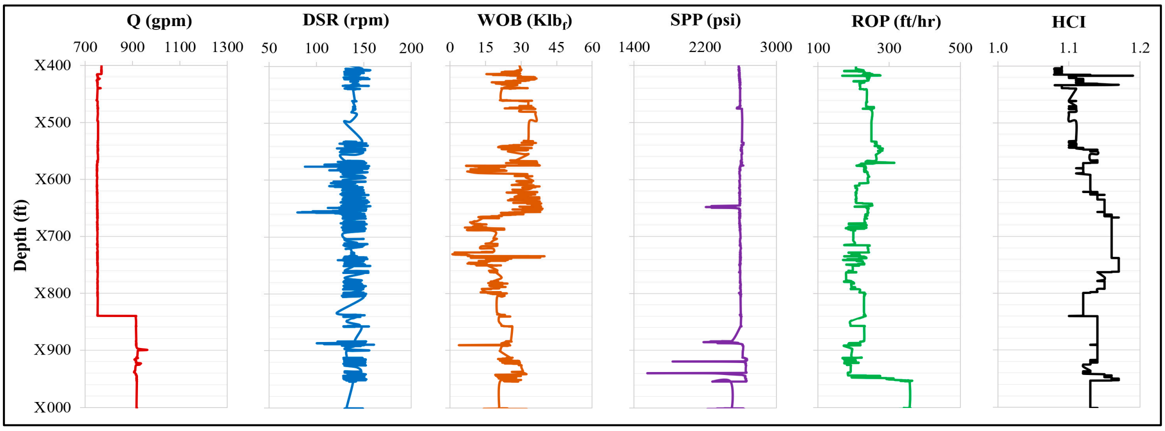

Figure 1. Changes in HCI and the drilling parameters for Well-A.

The crew also reported a decrease in erratic torque, which is an indication of removing the solids accumulated earlier at the bottom of the well. the crew members attempted to increase the drilling rate depending on real-time estimation of *HCI*. The changes in the drilling parameters and the associated *HCI* for this Case are shown in Figure 2. The crew noted that *HCI* indicates proper hole cleaning by evaluating the hole cleaning conditions at depths between X120 and X150 ft. Thus, they decided to increase *ROP* by applying more weight on bit *(WOB)* to increase well drillability, as shown in Figure 2. When *ROP* is increased *HCI* decreases due to an increase in the concentration of cuttings in the wellbore, as indicated in Figure 2.

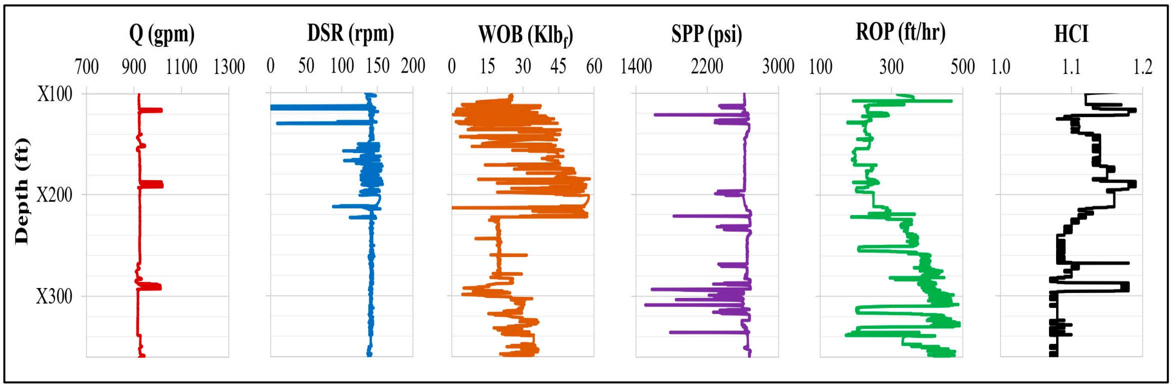

Figure 2. Changes in HCI and the drilling parameters for Well-A.

According to the driller, this trend also correlates with an increase in the drilling torque. As *HCI* values are still greater than 1.0 at a depth of X300, which is the minimum limit for proper hole cleaning, the driller decided to maintain the same *ROP* of 280 ft/h for drilling deeper sections. The crew did not report any stuck pipe problems during drilling and they were able to increase the drilling rate of this section based on the application of *HCI*.

Well-B,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 April 2023 doi:10.20944/preprints202304.0779.v1

The second well of this study is identified as offset Well-B where *HCI* was used to evaluate the deficiency of hole cleaning due to the cuttings accumulation and *HCI* was not employed for hole cleaning efficiency. The drilling parameters and *HCI* of are shown in Figure 3. The driller noted that the *HCI* is stable at approximately 1.13 for more than 100 ft, from X320 to X420 ft. At X420 ft *ROP* decreases considerably from 300 to 200 ft/h due to drilling through a hard formation.

However, as the hole was appropriately cleaned, the driller decided to apply more *WOB* to increase *ROP* again to approximately 300 ft/h. The crew noted that *HCI* gradually decreases when *ROP* begins to increase, indicating accumulation of cuttings. Hence, the driller was forced to increase the pumping rate of the drilling fluid from approximately 730 to almost 845 gpm, as indicated in Figure 3, to maintain a clean hole while drilling at a higher rate without encountering any pipe stuck problems.

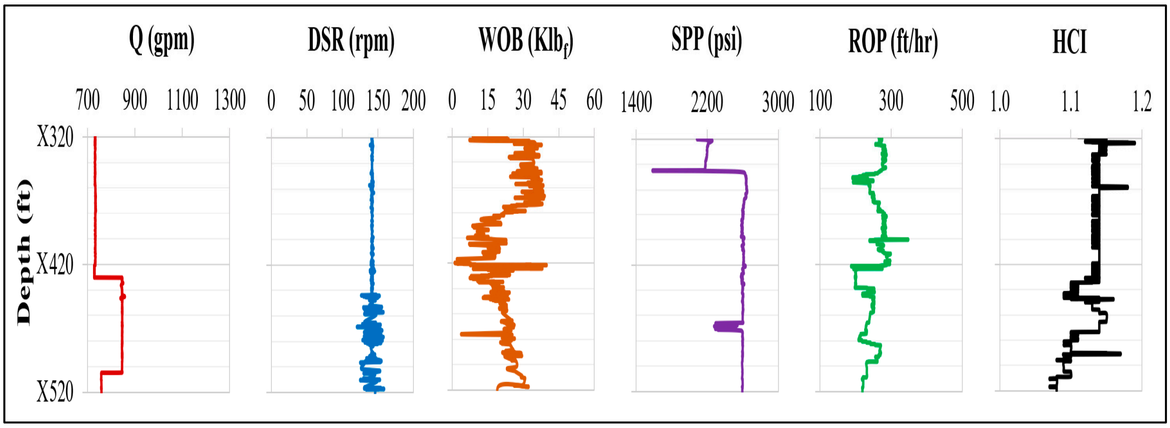

Figure 3. Changes in *HCI* and the drilling parameters for Well-B.

As the driller was aware that the bit would penetrate a soft formation at a depth of X160 ft, he decided to reduce *WOB* from 37 to 18 Klbf to prevent a significant increase in *ROP*. As indicated in Figure 4, even though *WOB* was significantly decreased to approximately one-third of its value, *ROP* in this soft formation increased only slightly from 200 to 240 ft/h. Even *HCI* increased by this change, which did not lead to cutting accumulation.

The drilling rate increases again from 240 ft to approximately 285 ft accompanied by a decrease of *HCI* from 1.14 to 1.06 without any change in *WOB* owing to the penetration of another softer formation. Despite this decrease in *HCI*, the driller decided not to reduce *WOB* to decrease the drilling rate as an *HCI* value of 1.06 is still in the safe zone to obtain appropriately clean holes.

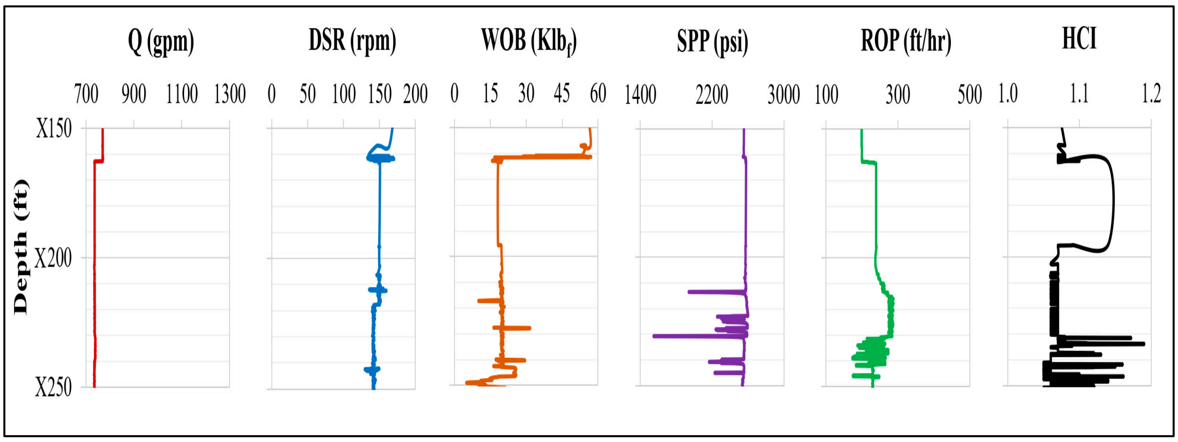

Figure 4. Changes in *HCI* and the drilling parameters for Well-B.

Table 9 summarizes the impact of implementation of HCI on well performance where was enhanced hole cleaning performed in well-A. HCI was having an average value more than 1, CA was

0.024 in well-A which less than 0.04 that was in well-B. The ultimate results showed average ROP improvement in well-A due to proper hole cleaning achievement.

Table 9. Impact of employing *HCI* on well performance.

Performance of Well-A employing *HCI*					
Items	Output	Minimum	Maximum	Average	Remark
1	*HCI*	0.8	1.9	1.5	Optimized hole cleaning efficiency
2	*CA*	0.012	0.039	0.024	Smooth cuttings accumulation in annulus removal due to optimized hole cleaning efficiency
3	*ROP*	120	280	205	Optimized drilling performance due to proper hole cleaning efficiency
Performance of an offset Well without employing *HCI*					
Items	Output	Minimum	Maximum	Average	Remark
1	*HCI*	0.3	1.3	0.81	Improper hole cleaning efficiency
2	*CA*	0.03	0.08	0.04	low removal of cuttings accumulation in annulus due to improper hole cleaning efficiency
3	*ROP*	100	260	135	low drilling performance due to insufficient hole cleaning efficiency

4. Conclusions

In this study, a hole cleaning index (*HCI*) was developed to optimize the hole cleaning and positively impact well drillability. It considers most of the influencing drilling parameters and the properties of the holes and drilling fluids. Hole cleaning chemistry and engineering parameters to understand hole cleaning efficiency and the process of optimization will help to fill the gaps in the knowledge of hole cleaning effectiveness, avoid drilling troubles and ensure a successful drilling. There are several points can be summarized as follows:

- High angle wells require specific hole cleaning strategies to ensure adequate transport of cuttings. Well design with minimized hole sizes and proper casing seat selections will maximize hole cleaning efficiency.
- Cuttings tend to accumulate in low side of drilled hole section in directional drilling where the annular velocity is significantly reduced. In addition, effort should be made to avoid enlargement of open holes. Use appropriate nozzles which balance ROP optimization versus annular velocity allowing cleaning of holes.
- Mud chemistry should ensure chemical compatibility to prevent wellbore problems such as tight hole, swelling shales etc. Wellbore stability is an important consideration to avoid hole enlargement (washout and break-out) achieved using a proper mud weight window.
- Mud rheology is selected to be high with a LSYP and enhanced low shear viscosity for wells with inclination higher than 35 degrees. ROP of instantaneous drill rate can be controlled to prevent overloading of the annulus with cuttings, especially with restricted circulation or while drilling blind. Viscous pills and dense pills should be used only when essential. Taking special care with Lo-Vis pills to maintain a high flow rate while dense pills are hole cleaning indicators. Use only when essential and limit volume to avoid fracture formation. Circulating and cleaning the hole section with rotation prior to tripping and a single application should be sufficient.
- The developed *HCI* was tested and validated in the field. The results demonstrated that the well drilling performance was improved by 50%. Implementing the new *HCI* and its automation would be a great addition to drilling best practices minimizing potential problems caused by insufficient hole cleaning.

Acknowledgments: The College of Petroleum and Geoscience, at King Fahd University of Petroleum & Minerals, is acknowledged for the support and permission to publish this work.

Conflict of Interest: There are no conflicts of interest.

Nomenclatures

DSR	Drill string Rotation
EMW	Equivalent Mud Weight
HCI	Hole Cleaning Index
K	Consistency Index
km	Modified Consistency Index
LSYP	Low Shear Yield Point
MW	Mud Weight
n	Flow behavior Index
nm	Modified Flow behavior Index
OD	Drill pipe outer diameter
OH	Open hole size
PV	Plastic Viscosity
R3	Viscometer reading at 3-RPM
R6	Viscometer reading at 6-RPM
ROP	Rate of Penetration
WOB	Weight on Bit
YP	Yield Point
α	Open hole angle
β	Open hole azimuth

References

Abedian, B., Science, M. K.-I. J. of E., and 2010, “On the Effective Viscosity of Suspensions,” Elsevier.
Aberoumand, S., Jafarimoghaddam, A., … M. M.-A. T., and 2016, “Experimental Study on the Rheological Behavior of Silver-Heat Transfer Oil Nanofluid and Suggesting Two Empirical Based Correlations for Thermal Conductivity And,” Elsevier.
Adari, R. B., Miska, S., Kuru, E., Bern, P., and Saasen, A., 2000, “Selecting Drilling Fluid Properties and Flow Rates for Effective Hole Cleaning in High-Angle and Horizontal Wells,” SPE Reserv. Eng. (Society Pet. Eng., (A), pp. 273–282.
Ahmed, A., Hayfaa, S., Hussien, A., … H. M.-55th U. R., and 2021, “Extensive Hole Cleaning Optimization to Mitigate Wellbore Instability Challenges in Shale Formations,” onepetro.org.
Alawami, M., Bassam, M., … S. G.-S. A. P. O., and 2020, “A Real-Time Indicator for the Evaluation of Hole Cleaning Efficiency,” onepetro.org.
Al-Azani, K., Elkatatny, S., Ali, A., Ramadan, E., and Abdulraheem, A., 2019, “Cutting Concentration Prediction in Horizontal and Deviated Wells Using Artificial Intelligence Techniques,” J. Pet. Explor. Prod. Technol., 9(4), pp. 2769–2779.
Alkinani, H., … A. A.-H.-S. E. R., and 2019, “Application of Descriptive Data Analytics: How to Properly Select the Best Ranges of Viscosity and Flow Rate for Optimal Hole Cleaning?,” onepetro.org.
Al-Rubaii, M., Gajbhiye, R., … A. A.-Y.-I., and 2020, “Automated Evaluation of Hole Cleaning Efficiency While Drilling Improves Rate of Penetration,” onepetro.org.
Alsaba, M. T., Al Dushaishi, M. F., and Abbas, A. K., 2020, “Application of Nano Water-Based Drilling Fluid in Improving Hole Cleaning,” SN Appl. Sci., 2(5).
Azar, J.J., 1990, July. Does Mud Rheology Play a Major Role in Hole Cleaning of Highly deviated Wells?. In Latin American Drilling Conference.
Beck, F., Powell, J., Conference, M. Z.-S. D., and 1995, “The Effect of Rheology on Rate of Penetration,” onepetro.org.
Becker, T., Azar, J., Engineering, S. O.-S. D., and 1991, “Correlations of Mud Rheological Properties with Cuttings-Transport Performance in Directional Drilling,” onepetro.org.

Berg, E., Sedberg, S., Kaarigstad, H., … T. O.-I. D., and 2006, “Displacement of Drilling Fluids and Cased-Hole Cleaning: What Is Sufficient Cleaning?,” onepetro.org.
Bern, P., Zamora, M., Slater, K., … P. H. technical conference, and 1996, “The Influence of Drilling Variables on Barite Sag,” onepetro.org.
Conference, M. R.-I. D., and 1994, “Hole Cleaning in Large, High-Angle Wellbores,” onepetro.org.
Deng, S., 2018, “Assessment of Drilling Fluid Hole Cleaning Capacity in Horizontal Directional Drilling–A Parametric Study of the Effects of Drilling Fluid Additives.”
DRILLING, M.F.I. and PIGOTT, R., 1935. MUD FLOW IN DRILLING 91. Drilling and Production Practice, 1934, p.91.
Einstein, A., 1906. A new determination of molecular dimensions. Ann. Phys., 19, pp.289-306.
Elkatatny, S., Kamal, M., Alakbari, F., Rheology, M. M.-A., and 2018, “Optimizing the Rheological Properties of Water-Based Drilling Fluid Using Clays and Nanoparticles for Drilling Horizontal and Multi-Lateral Wells,” degruyter.com.
Finger, J., and Blankenship, D., 2012, “Handbook of Best Practices for Geothermal Drilling.”
Fjaer, E., Holt, R., Horsrud, P., and Raaen, A., 2008, Petroleum Related Rock Mechanics.
Frenkel, H., Levy, G., Minerals, M. F.-C. and C., and 1992, 1992, “Clay Dispersion and Hydraulic Conductivity of Clay-Sand Mixtures as Affected by the Addition of Various Anions,” Springer, 40(5), pp. 515–521.
Gamal, H., Elkatatny, S., Basfar, S., Sustainability, A. A.-M.-, and 2019, “Effect of PH on Rheological and Filtration Properties of Water-Based Drilling Fluid Based on Bentonite,” mdpi.com.
Guo, B., and Liu, G., 2011, Applied Drilling Circulation Systems: Hydraulics, Calculations and Models.
Hossain, M.E. and Al-Majed, A.A., 2015. Fundamentals of sustainable drilling engineering. John Wiley & Sons.
Hossain, M.E. and Islam, M.R., 2018. Drilling Engineering Problems and Solutions: A Field Guide for Engineers and Students. John Wiley & Sons.
Huaizhong, S., … Z. H.-J. of, and 2019, “Numerical Simulation and Experimental Study of Cuttings Transport in Narrow Annulus,” asmedigitalcollection.asme.org.
Hussaini, S. M., and Azar, J. J., 1983, “EXPERIMENTAL STUDY OF DRILLED CUTTINGS TRANSPORT USING COMMON DRILLING MUDS.,” Soc. Pet. Eng. J., 23(1), pp. 11–20.
Hyun, C., Shah, S., and Osisanya, S., 2007, “Effects of Fluid Flow in a Porous Cuttings-Bed on Cuttings Transport Efficiency and Hydraulics.”
Jimmy, D., Wami, E., International, M. O.-S. N. A., and 2022, “Cuttings Lifting Coefficient Model: A Criteria for Cuttings Lifting and Hole Cleaning Quality of Mud in Drilling Optimization,” onepetro.org.
Jorge Silva Ferreira, E., José António de Almeida Associado, D., Ana Paula Fernandes da Silva Arguente, D., Paulo do Carmo Sá Caetano Vogal, D., and José António de Almeida, D., 2012, “Hole Cleaning Performance Monitoring during the Drilling of Directional Wells.”
Laik, S., 2018, Offshore Petroleum Drilling and Production.
Lavrov, A., and Torsaeter, M., 2016, “Physics and Mechanics of Primary Well Cementing.”
Li, J., and Walker, S., 1999, “Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells.”
Luo, Y., Bern, P., Conference, B. C.-I. D., and 1992, “Flow-Rate Predictions for Cleaning Deviated Wells,” onepetro.org.
Mahmoud, A., … M. E.-J. of E., and 2020, “New Hybrid Hole Cleaning Model for Vertical and Deviated Wells,” asmedigitalcollection.asme.org.
Malekzadeh, N., and Mohammadsalehi, M., 2011, “Hole Cleaning Optimization in Horizontal Wells, a New Method to Compensate Negative Hole Inclination Effects,” Soc. Pet. Eng. - Brazil Offshore Conf. 2011, 2, pp. 627–637.
McCollum, F., … A. K.-I. A. P., and 1998, “Mud Reformulation and Solids Control Equipment Upgrades Improve Hole Cleaning and Reduce Environmental Discharges-A Case Study,” onepetro.org.
Mitchell, B., 1992, “Advanced Oilwell Drilling Engineering Handbook.”
Mitchell, J., 2001. Trouble-free drilling. Woodlands, TX: Drilbert Engineering.
Moore, P., 1986, “Drilling Practices Manual.”
Murtaza, M., Tariq, Z., Mahmoud, M., Kamal, M. S., and Al Shehri, D., 2021, “Application of Anhydrous Calcium Sulfate as a Weighting Agent in Oil-Based Drilling Fluids,” ACS Omega, 6(33), pp. 21690–21701.
Newitt, D.M., Richardson, J.F. and Gliddon, B.J., 1961. Hydraulic conveying of solids in vertical pipes. Trans. Instn. Chem. Engrs, 39, pp.93-100.
O’brien, T., Conference, M. D.-S. D., and 1985, “Hole Cleaning: Some Field Results,” onepetro.org.

Ofei, T., Lund, B., … K. G.-A. T. N. R., and 2020, "Effect of Barite on the Rheological Properties of an Oil-Based Drilling Fluid," researchgate.net.
Ogunrinde, J. O., and Dosunmu, A., 2012, "Hydraulics Optimization for Efficient Hole Cleaning in Deviated and Horizontal Wells," Soc. Pet. Eng. - 36th Niger. Annu. Int. Conf. Exhib. 2012, NAICE 2012 - Futur. Oil Gas Right Balanc. with Environ. Sustain. Stakeholders' Particip., 1, pp. 100–115.
Okrajni, S. S., and Azar, J. J., 1986, "EFFECTS OF MUD RHEOLOGY ON ANNULAR HOLE CLEANING IN DIRECTIONAL WELLS.," SPE Drill. Eng., 1(4), pp. 297–308.
Peden, J. M., Ford, J. T., and Oyeneyin, M. B., 1990, "Comprehensive Experimental Investigation of Drilled Cuttings Transport in Inclined Wells Including the Effects of Rotation and Eccentricity," Eur. Pet. Conf., 1, pp. 393–404.
Pedrosa Consicion, H.C., Lund, B., Opedal, N.V.D.T., Ytrehus, J.D. and Saasen, A., 2022. Experimental Bench-Scale Study on Cuttings-Bed Erosion in Horizontal Wells. ASME
Ramsey, M., 2019, Practical Wellbore Hydraulics and Hole Cleaning: Unlock Faster, More Efficient, and Trouble-Free Drilling Operations.
Ravi, K., and Hemphill, T., 2006, "Pipe Rotation and Hole Cleaning in Eccentric Annulus," Proc. IADC/SPE Drill. Conf.
Robinson, L. and Morgan, M., 2004, April. Effect of hole cleaning on drilling rate and performance. In AADE 2004 Drilling Fluids Conference (pp. 6-7).
Rubaii, M. Al, Gajbhiye, R., … A. A.-O. T., and 2020, "A New Automated Cutting Volumes Model Enhances Drilling Efficiency," onepetro.org.
Saasen, A., Omland, T., Ekrene, S., … J. B.-S. drilling &, and 2009, 2009, "Automatic Measurement of Drilling Fluid and Drill-Cuttings Properties," onepetro.org.
Saihati, A., Elkatatny, S., Mahmoud, A. A., Abdulraheem, A., and Alsaihati, A., 2021, "Use of Machine Learning and Data Analytics to Detect Downhole Abnormalities While Drilling Horizontal Wells, with Real Case Study," asmedigitalcollection.asme.org.
Sanchez, R. A., Azar, J. J., Bassal, A. A., and Martins, A. L., 1999, "Effect of Drillpipe Rotation on Hole Cleaning during Directional-Well Drilling," SPE J., 4(2), pp. 101–108.
Sargani, H., Tunio, A., 2277–4106, Z. H.-E.-I., P-ISSN, and 2020, 2020, "Investigating the Impact of Oil Water Ratio on Rheological Properties of Biodiesel Based Drilling Mud," researchgate.net, 10(1).
Shariff, M., Nakamura, D., Technol, M. Y.-S. A. J., and 2007, "An Experimental Study of Hole Cleaning Under Simulated Downhole Conditions," academia.edu.
Shirangi, M. G., Aragall, R., Ettehadi Osgouei, R., Gharib Shirangi Baker Hughes Houston, M., Roger Aragall Baker Hughes Celle, T., Reza Ettehadi Baker Hughes Houston, G., Roland May Baker Hughes Celle, T., Edward Furlong Baker Hughes Houston, G., Thompson Jr, T., Baker Hughes Houston, C. A., and Thomas Dahl, T. G., 2021, "Development of Digital Twins for Drilling Fluids: Local Velocities for Hole Cleaning and Rheology Monitoring," asmedigitalcollection.asme.org.
Sifferman, T. R., and Becker, T. E., 1992, "Hole Cleaning in Full-Scale Inclined Wellbores," SPE Drill. Eng., 7(2), pp. 115–120.
Stephens, M., Swaco, M.-I., Gomez-Nava, S., and Churan, M., 2009, "AADE 2009-NTCE-11-04: Laboratory Methods to Assess Shale Reactivity with Drilling Fluids."
Technical, M. A. R.-S. K. of S. A. A., and 2018, 2018, "A New Robust Approach for Hole Cleaning to Improve Rate of Penetration," onepetro.org.
Technology, R. S. E. R., and 2013, "Modeling and Analysis of Drillstring Vibration in Riserless Environment," asmedigitalcollection.asme.org.
Terab, A., Bashier, M., Saleh, M., and Bagadi, M., 2016, "Hole Cleaning Modelling & Simulation In Horizontal Wells Case Study Heglig Field."
Tomren, P. H., Iyoho, A. W., and Azar, J. J., 1986, "EXPERIMENTAL STUDY OF CUTTINGS TRANSPORT IN DIRECTIONAL WELLS.," SPE Drill. Eng., 1(1), pp. 43–56.
Vanessa Boyou, N., Ismail, I., Rosli Wan Sulaiman, W., Sharifi Haddad, A., Husein, N., Thin Hui, H., and Nadaraja, K., 2019, "Experimental Investigation of Hole Cleaning in Directional Drilling by Using Nano-Enhanced Water-Based Drilling Fluids," Elsevier.
Whittaker, A., 1985, Theory and Application of Drilling Fluid Hydraulics.

 doi:10.20944/preprints202304.0779.v1

Ytrehus, J. D., Lund, B., Taghipour, A., Kosberg, R., Trondheim, S., Luca, N., Aker, C., Stavanger, B. P., Knud, N., Schlumberger, R. G., Stavanger, M.-S., and Saasen, N. A., 2019, "Hydraulic Behavior in Cased and Open-Hole Sections in Highly Deviated Wellbores," asmedigitalcollection.asme.org.
Ytrehus, J., Lund, B., … A. T.-J. of, and 2021, "Oil-Based Drilling Fluid's Cuttings Bed Removal Properties for Deviated Wellbores," asmedigitalcollection.asme.org.
Zamora, M., Roy, S., Conference, K. S.-A. 2005 N. T., and 2005, "Comparing a Basic Set of Drilling Fluid Pressure-Loss Relationships to Flow-Loop and Field Data," aade.org.
Zhou, Z., 1997, "Swelling Clays in Hydrocarbon Reservoir: The Bad, the Less Bad, and the Useful."
Zoback, M., 2010, Reservoir Geomechanics.