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Experimental Bench-Scale Study on Cuttings-Bed Erosion in Horizontal Wells

Cuttings-beds formation while drilling wellbores is a common challenge, especially for horizontal wells, as drilled particles have higher area to be deposited and form cuttings-beds, which can cause several problems such as increased torque and drag, pipe sticking or pipe breakage, among others. Removal of the drilled cuttings is done by circulating a suitable drilling fluid through the wellbore. This paper presents results from laboratory tests with deposited cuttings-bed and the flow of a fluid to erode the bed. The simulated cuttings-bed is a 1 m long deposited sand-bed in a horizontal section. Three different types of fluids are being used in the tests. To investigate how the rheological properties can affect the erodibility of the cuttings-bed, water (as a Newtonian fluid), a xanthan gum solution, and a water-based drilling fluid prepared for an offshore field operation (as a non-Newtonian fluids) are applied. Ultrasound measurements together with differential bed weight have been used to analyze the fluid–bed interaction. Results have shown that the cuttings-bed is eroded by dune movement. Saltation and dragging of sand particles due to the fluid flow appear to create a crest and then avalanche them down. The different types of fluids undergo different shear rates from the same pump power as the viscosity changes, as well as flow rates dependency along the dune extent. [DOI: 10.1115/1.4056337]

Keywords: drilled cuttings, transport efficiency, cuttings-bed removal, oil/gas reservoirs, petroleum engineering, petroleum wells-drilling/production/construction

1 Introduction

As more complex wellbores are being drilled, such as highly deviated or extended reach horizontal wells, drilled cuttings deposition along the well becomes more challenging and problematic to handle. These drilling cuttings are rock debris composed mainly by sandstones and shales with specific gravities between 2.2 and 2.7, with an average of 2.6, and sizes varying widely between a dozen of microns to tens of millimeters [1]. Efficient drilled cuttings removal has been studied for decades as inadequate cuttings transport remains a challenge as wellbore trajectory become more complex. Drilled cuttings need to be transported out to the surface to safely continue drilling. Poor hole cleaning efficiency might lead to reduced rate of penetration (ROP), formation fracturing, premature bit wear, increased drill-string drag and torque, stuck pipe, or even pipe breakage.

Several studies indicate that cuttings transport phenomena are controlled by three main parameters: (1) operational parameters include drill pipe rotation, hole inclination, annular-eccentricity, fluid flowrate, and ROP, (2) drilling fluid parameters, such as rheological parameters, density, and composition, and (3) cuttings' parameters, which include size, shape, and type, although there are still some gaps to be covered specially regarding the relationship between the previous parameters [2], in addition to those parameters that can be controlled, pressure and temperature also have shown to influence the cuttings transport [3].

Drilling fluids play an important role in drilling operations and wellbore cleaning efficiency as the drilled cuttings are transported out to the surface through the circulating drilling fluid. The transport distance for debris can be long and it is likely that debris is both in suspension and in contact with wellbore or cuttings-bed during the removal operation. It has been shown that in horizontal wells, higher flowrates improve the cleaning performance [4], although it is important to note that excessive high fluid velocity can cause erosion problems to enlarge the wellbore.

It is therefore important to not only study the behavior of the parameters by themselves but also to understand the combined behavior and properties of the drilled cuttings, the formed cuttings-beds, and the drilling fluid.

In addition, it has been described that for horizontal wells [5], the dominating driving force for transport phenomena is dragging, while lifting plays a minor role. To disturb the deposited cuttings-bed by dragging or lifting, it is necessary for the cleaning fluid to reach and exceed a critical flow velocity and critical shear stress for bed erosion [6], which is calculated using Shields' number (θ), being the ratio between the shear forces trying to remove the particles and gravity forces trying to keep the particles in the bed:

$$\theta_c = \frac{\tau_c}{(\rho_s - \rho_f) g d_p} = \frac{\tau_c}{\Delta \rho g d_p} \tag{1}$$

A critical value θ_c of Shield's number is defined for onset of particle transport. For laminar flow, the value has been reported to be about 0.12, while for turbulent flow it is about half of this value.

The bed shear stress is calculated using the Haaland friction factor (f_H) correlations for turbulent flow with different values of wall roughness, based on the Reynolds number (Re), where k is the absolute wall roughness and D is the diameter.

$$\frac{1}{\sqrt{f_H}} = -3.6 \log_{10}\left[\frac{6.9}{\mathrm{Re}} + \left(\frac{k}{3.7D}\right)^{10/9}\right] \tag{2}$$

These calculations give the possibility to predict and explain the erodibility behavior of the cuttings-bed at arbitrary flowrates of the cleaning fluid, by tailoring Shield's number according to the different interstitial fluids of the cuttings-bed. Furthermore, previous experimental studies have shown the flow velocity and flow

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Contributed by the Petroleum Division of ASME for publication in the Journal of Energy Resources Technology. Manuscript received June 21, 2022; final manuscript received October 17, 2022; published online December 14, 2022. Assoc. Editor: Saeed Salehi.

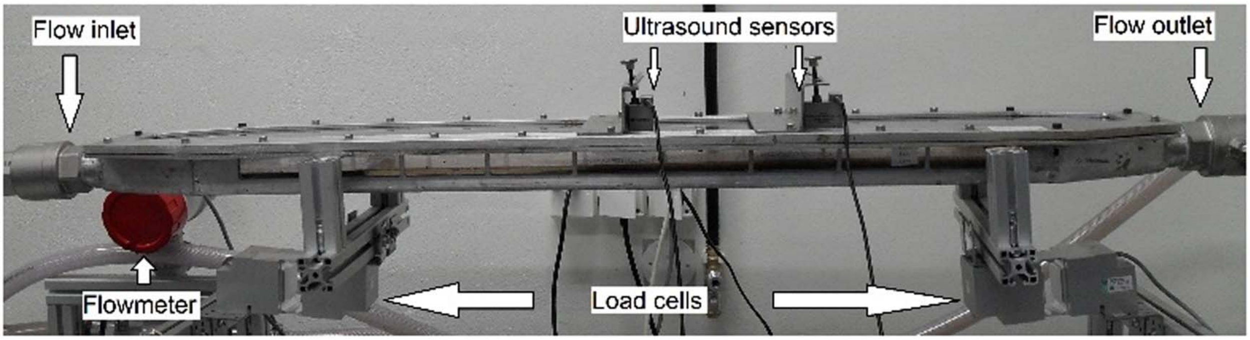

Fig. 1 Bench-scale setup picture

regime importance to move the particles from a bed [7].

It has been demonstrated that cuttings-bed formed by different interstitial fluids show distinct particle movement behavior [8], mainly due to the internal friction imparted by the fluid to the particles in the bed [9], as well as the hydraulically surface roughness and the degree of boundary slip imparted by the wetting system [10].

2 Materials and Methods

The experiments are conducted in a bench-scale setup shown in Fig. 1. This setup is a 120 cm rectangular container which is 75 cm long, 15 cm wide, and 2 cm height bed formed by quartz sand particles in the range from 1.1 mm to 1.6 mm and an interstitial fluid to simulate the cuttings-bed wetted by the drilling fluid. This leaves a gap of 3 cm for the cleaning fluid to flow.

Three fluids were used as interstitial fluids to simulate the formed cuttings-bed: water, 0.5% w/w xanthan gum solution, and a field water-based drilling fluid (WBM) with density of 1.68 g/cm^3 containing KCl, soda ash, polyanionic cellulose, starch, xanthan gum, and barite. Tap water as cleaning fluid has been used to erode the formed cuttings-bed.

The experimental setup shown in detail in Fig. 2 consists of the following main components:

– Storage tank for the cleaning fluid (fluid tank)
– Cleaning fluid pump
– Recirculating pump
– Flowmeter
– Load cells (weight meter)
– Erosion cell
– Sand deposit tank (settling tank)
– Waste tank
– Velocity profile and bed height ultrasound meters

The cleaning fluid is pumped through the erosion cell, with the cuttings-bed already formed, at a low flowrate, 0.17 ± 0.5 m/s, to stabilize the system without removing sand particles. Once the system is considered stable, the flowrate is increased to eroding velocities. Such flowrate is maintained between 1 min and 1.5 min.

The flowrate is controlled at the rate needed to provoke bed erosion and the fluid containing eroded particles are led to a settling tank to separate the particles from the fluid. After separation, the fluid is recirculated back to the cleaning fluid storage tank and is ready for new tests. Bed erosion is measured by bed height and weight change within the erosion cell.

The circulation system is closed such that the cleaning fluid can be used and recirculated without disturbance. In addition, the sides and the top of the erosion cell have transparent parts for visual inspection of the flow and bed behavior. Ultrasound transducers are also mounted on top to measure the bed height and to obtain velocity profile.

Statistical tools coded in PYTHON have been used to plot and analyze the data. Flowrate, time, and wetting fluid type are independent variables and removed bed weight is the dependent variable. The interaction between the parameters is then observed.

2.1 Bed-Wetting Fluid Characterization. To determine the general flow behavior, the bed-wetting fluids' viscosity profile was characterized through a flow curve obtaining a fitting formula to describe it (see Fig. 3). The plotted data are derived from analysis performed with a rheometer, Anton-Paar MCR102, equipped with a grooved Couette geometry to avoid slippage. The samples were initially pre-sheared at 1000 s^{-1} for 120 s to reach steady-state shear viscosity. After this, a measurement protocol was started with a ramp down from 1200 s^{-1} to 60 s^{-1} in 100 linear steps, followed

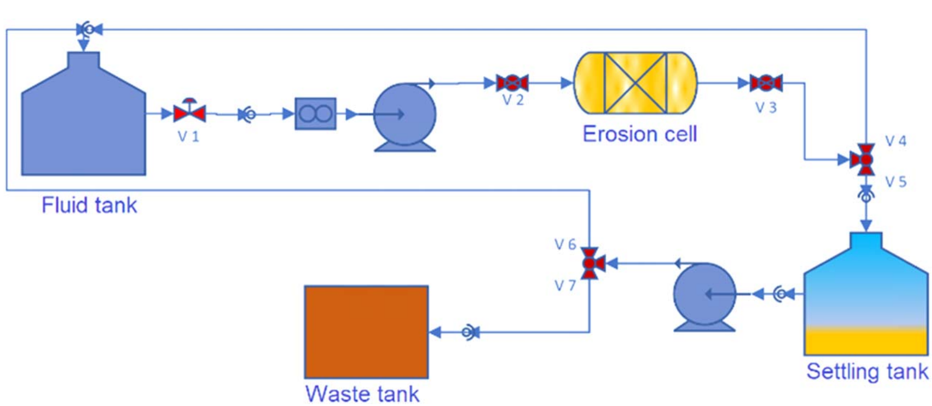

Fig. 2 Bench-scale setup schematic

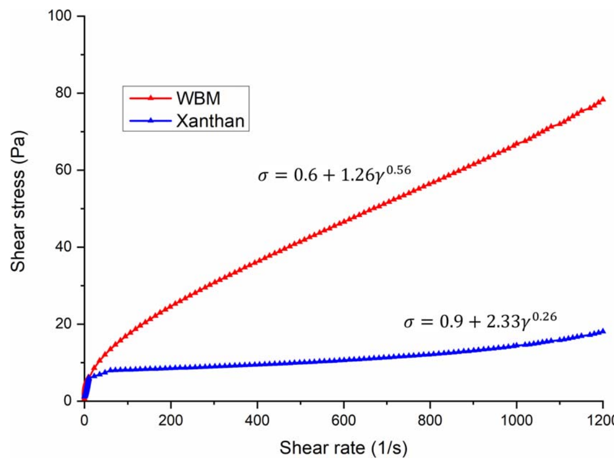

Fig. 3 Bed-wetting fluids' flow curve

by five linear steps from 60 s^{-1} to 10 s^{-1}, and finally with 100 linear steps from 10 s^{-1} to 0.1 s^{-1}. The measuring time per point was set to 2 s.

The Hershel–Buckley model best describe the water-based drilling fluid and the xanthan gum solution. In addition, higher viscosity profile is shown by the water-based drilling fluid in comparison to the xanthan gum solution, and these two are much higher than water which is a Newtonian fluid with viscosity around 1 MPa s.

In addition to the flow curves, the viscoelastic behavior was analyzed by the use of oscillatory measurements (see Fig. 4). The frequency was set to 1 Hz and the amplitude increased logarithmically from 0.001% to 100% strain with 60 measuring points. The storage modulus (G') and loss modulus (G'') curves characterized the material's elastic and viscous contribution to the complex viscosity, respectively.

When G' is higher than G'', the elastic behavior dominates over the viscous behavior, thus the fluid shows more of a solid-like performance. The G'' to G' ratio gives a measure of the stiffness of the material and defines the gel property of the fluid sample. In the case where G'' is higher than G', the viscous behavior dominates over the elastic behavior and the sample acts as liquid-like. The cross-over point ($G' = G''$) is called the flow point. The length of the linear viscoelastic range (LVER) indicates the minimum strain to initiate breakage of the inner structure.

Even though the water-based drilling fluid showed higher flow curve in comparison to the xanthan gum, the last one had a higher LVER, meaning that it behaves solid-like for higher stresses, thus it requires a higher initial stress for the fluid to start flowing.

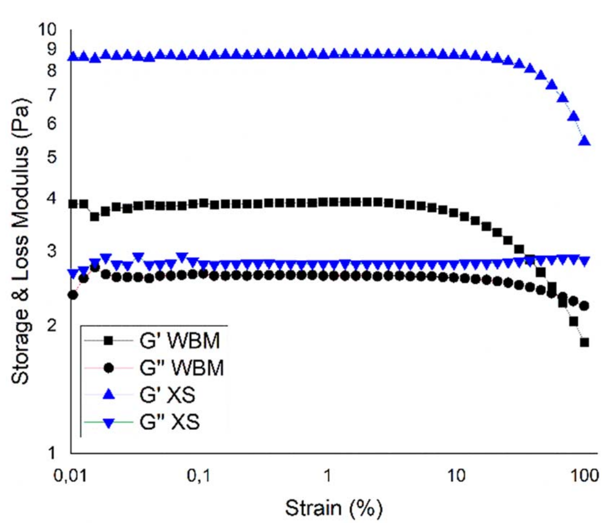

Fig. 4 Bed-wetting fluids' viscoelastic behavior

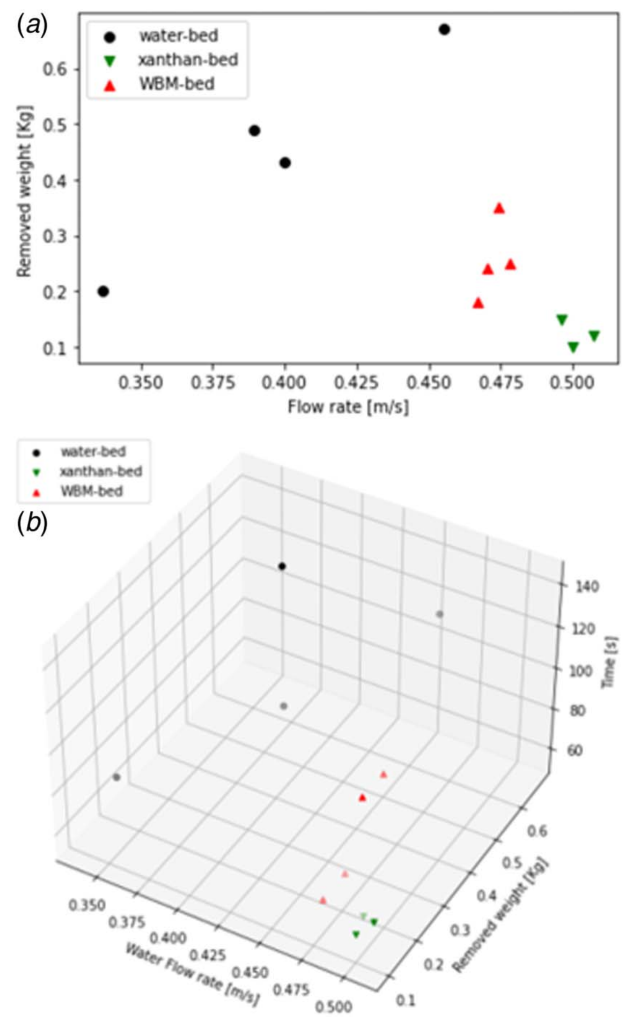

Fig. 5 Cuttings-bed removed weight as function of flowrate is plotted for three interstitial fluid cases

3 Results and Discussion

The effect of the interstitial fluid that confirms the cuttings-bed has been analyzed in terms of removed weight of the cuttings-bed while wetted by the different fluids. In Fig. 5(*a*), the removed weight of the formed cuttings-bed versus the flowrate of the cleaning fluid is plotted, after the elapsed time shown in Table 1, as

Table 1 Experimental data

Bed type	Flowrate (m/s)	Reynolds	Time (s)	Removed weight (kg)
W-b	0.389	19,378	144	0.49
W-b	0.337	16,795	70.5	0.2
W-b	0.455	22,700	114	0.67
W-b	0.4	19,932	89	0.43
X-b	0.496	24,730	60.5	0.15
X-b	0.5	24,915	61.5	0.1
X-b	0.507	25,280	66.5	0.12
WB-b	0.478	23,810	96.5	0.25
WB-b	0.47	23,440	58	0.24
WB-b	0.467	23,250	54	0.18
WB-b	0.474	23,620	90.5	0.35

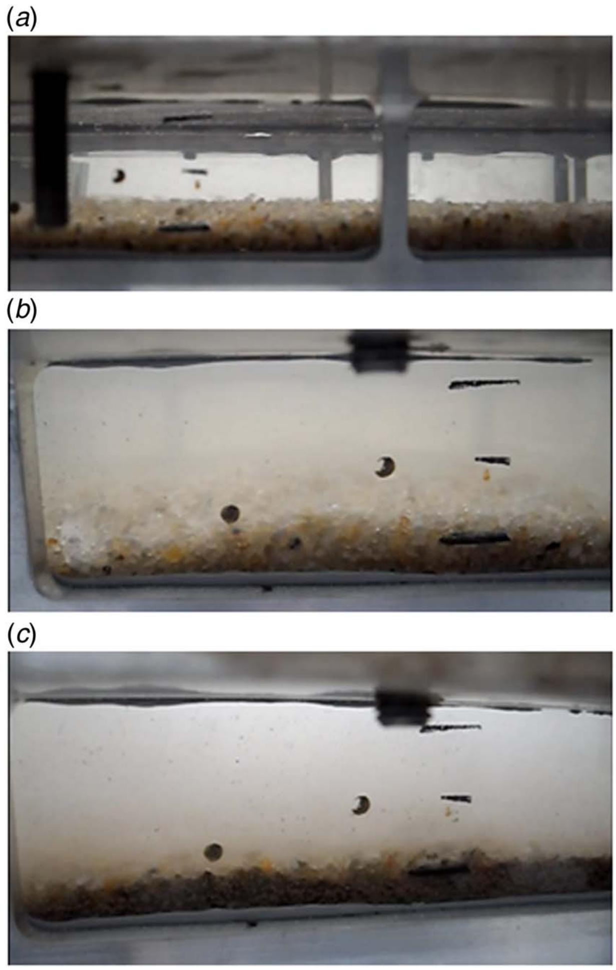

Fig. 6 Visualization of the particle movement displaced by water in cuttings-bed wetted by (*a*) water, (*b*) xanthan gum solution, and (c) water-based drilling fluid

shown in Fig. 5(*b*), for each type of cuttings-bed wetted by the specified interstitial fluid.

The cuttings-bed wetted by water requires less flowrate to remove a similar amount of the bed, in comparison to the cuttings-bed wetted by xanthan gum solution and the water-based drilling fluid (Fig. 6).

The test data show that the cuttings-bed wetted by a xanthan gum solution was more difficult to remove by the flow as less bed weight was removed even though the flowrate was significantly higher during the tests. One hypothesis is that the interstitial fluid imparts cohesive forces to the sand particles. When the particles are surrounded by the interstitial fluid, these cohesive forces have a longer reach due to the viscoelasticity of the fluid.

The previously mentioned hypothesis would explain why the cuttings-bed wetted by the xanthan gum solution present higher cohesion forces. Following this, also why it requires higher flowrate to reach removed bed weight similar to the cuttings-bed wetted by the WBM. This can be due to the larger linear viscoelastic range that the xanthan gum solution demonstrates compared to that of the water-based drilling fluid. Thus, it is more difficult to start internal movement within the cuttings-bed when it is at quiescent state.

The data obtained from the setup are shown in Table 1, where the three variables are bed type as a categorical variable, and flowrate and time as continuous variables, the time shown is the time that the water was circulated through the erosion cell, and this was limited due to the tanks capacity, and the response is removed weight. The bed type is defined as W-b, for the cuttings-bed wetted by water, X-b for the cuttings-bed wetted by the xanthan gum solution, and WB-b for the cuttings-bed wetted by the water-based drilling fluid .

Ordinary least-squares method was used in PYTHON to obtain a predictive linear equation model involving the variables and response measured, and in addition, information on the statistical relevance of the variables and likelihood of model fitting.

Table 2 shows all the information related to the ordinary least-squared regression. In Table 2, it is shown that the number of observations is 11 and the residual degrees of freedom is 6. The R^2 value of 0.962 is a good fit and the fact that the adjusted R^2 is lower means one of the variables might not be completely relevant.

The F-statistic value of 37.88 and the P-value of the F-statistics close to 0, in our case 0.000215, mean that the obtained model has a linear relationship between the variables.

By looking at the variables in a separate manner, a coefficient value of each of the variables is obtained to create a model. This model is shown in Eq. (3).

$$y = -1.029 - 0.401WB - 0.6091X + 3.3173v + 0.0016T \tag{3}$$

where y is the removed bed weight in kg; WB is the usage of water-based drilling fluid as the wetting fluid, which has a value of 0 when is not in use and a value of 1 when used; X is the usage of xanthan gum solution as wetting fluid, which has a value of 0 when is not in use and 1 when used; v is the flowrate in m/s; and T is the time in seconds. These two factors have a negative sign because when any of them is used, the removed bed weight is lower in comparison to water as the wetting fluid.

The model created is specific for these conditions of geometry, cuttings-bed types, and cleaning fluids and should not be used in other conditions, and to analyze other conditions, a new model

Table 2 Ordinary least-squared results summary

Dep. variable	Removed_weight	R^2	0.962
Model	OLS	Adj. R^2	0.937
Method	Least-squares	F-statistic	37.88
Date	Wed, 15 Dec. 2021	Prob (F-statistic)	0.000215
Time	17:58:12	Log-likelihood	21.881
No. observations	11	AIC	−33.76
Df residuals	6	BIC	−31.77
Df model	4		
Covariance type	Nonrobust		

	Coef	Std err	t	$P>\|t\|$	[0.025	0.975]
Intercept	−1.0291	0.212	−4.844	0.003	−1.549	−0.509
Bed_type[T.WB-b]	−0.401	0.067	−5.975	0.001	−0.565	−0.237
Bed_type[T.X-b]	−0.6091	0.089	−6.876	0	−0.826	−0.392
Flow_rate	3.3173	0.594	5.586	0.001	1.864	4.77
Time	0.0016	0.001	2.116	0.079	0	0.003

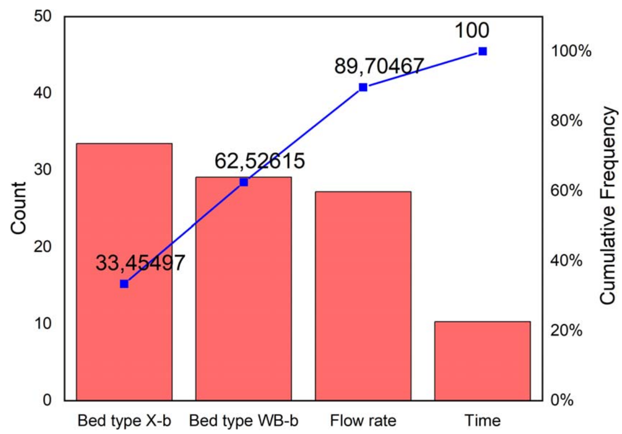

Fig. 7 Factors' and interactions contributions in the model

should be created by performing another analysis of variance (ANOVA) test with the required conditions.

By looking at the *t*-test of each variable including the intercept, it is possible to observe that all of them are higher in magnitude than 0. At the same time, the *P*-value corresponding for each *t*-test is possible to observe that all the variables except the time are lower than 0.05 and close to 0 which means that these variables are significant and independent in the model. The time variable, even with a *t*-test higher than the unit of magnitude, has a *P*-value higher than 0.05, which means that it is not completely significant in the model. This could be because the time difference is not very high.

The factors' interaction contribution to remove weight from the bed is plotted in a pareto chart for easier understanding (see Fig. 7), showing the percentage in impact that each variable has in order to remove cuttings. This chart shows that the fluid type wetting the cuttings-bed plays the most significant role to remove particles from a cuttings-bed. Complementing the numerical value information with the *t*-test negative sign, it can be concluded that the use of xanthan gum solution as the wetting fluid is the factor that has the higher significance to reduce the removal efficiency. The next most significant effect comes from the use of water-based drilling fluid as the wetting fluid.

If the fluid type that is wetting the cuttings-bed is disregarded, we corroborate that the factor that affects the cuttings removal most is the flowrate [11]. This is the case in a situation like the one simulated here, where no drill-string rotation is present. It is known that drill-string rotation increases the cuttings transport efficiency significantly [12] and often more than the flowrate. However, rotation is not considered here.

4 Conclusion

The interstitial fluid is wetting the cuttings-bed and modifies greatly the internal bonding forces within the bed itself. It is important to understand more deeply the cuttings-bed characteristics and not only evaluate the viscous properties of the drilling fluid to optimize hole cleaning efficiency.

Cuttings-bed formed by different types of wetting fluids have different erodibility behavior, even though they are built with the same type of solid particles and are subjected to similar flowrates.

Mathematical models can help to predict the drilled cuttings removal efficiency from a bed situation according to the significance of each factor involved in the operation.

Acknowledgment

This work was carried out at SINTEF's laboratory. The authors thank the Research Council of Norway (through grant 294688), OMV, and Equinor for financing this study. The authors also thank Schlumberger M-I Swaco fluids for supply of, and technical assistance with, the fluids and chemicals used in the study. The experimental work has been carried out with the use of the R&D Infrastructure Norwegian P&A Laboratories (NorPALabs). The authors acknowledge the financial support from the Research Council of Norway (RCN) for the establishment of the Norwegian P&A Laboratories (RCN project award no. 296009).

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

A = cross-sectional area
P = wetted perimeter of the setup
V = fluid velocity
F_h = Haaland friction factor
G' = storage modulus
G'' = loss modulus
Re = Reynold's number
θ_c = critical Shield's number
μ = kinematic viscosity
ρ_s = cuttings' density
ρ_f = fluid density
τ_c = critical shear stress

References

[1] Nazari, T., Hareland, G., and Azar, J. J., 2010, "Review of Cuttings Transport in Directional Well Drilling: Systematic Approach," SPE Western Regional Meeting, Anaheim, CA, May 27–29, p. 15.
[2] Pedrosa, C., Saasen, A., and Ytrehus, J. D., 2021, "Fundamentals and Physical Principles for Drilled Cuttings Transport—Cuttings Bed Sedimentation and Erosion," Energies, **14**(3), p. 545.
[3] Akbari, S., and Hashemabadi, S. H., 2017, "Temperature and Pressure Effects of Drilling Fluid on Cutting Transport Using CFD Simulations," Asia–Pac. J. Chem. Eng., **12**(6), pp. 980–992.
[4] Mohammadzadeh, K., Akbari, S., and Hashemabadi, S. H., 2021, "Parametric Study of Cutting Transport in Vertical, Deviated, and Horizontal Wellbore Using CFD Simulations," Pet. Sci. Technol., **39**(2), pp. 31–48.
[5] Bizhani, M., and Kuru, E., 2018, "Critical Review of Mechanistic and Empirical (Semimechanistic) Models for Particle Removal From Sandbed Deposits in Horizontal Annuli With Water," SPE J., **23**(2), pp. 237–255.
[6] Li, J., and Luft, B., 2014, "Overview of Solids Transport Study and Application in Oil-Gas Industry—Theoretical Work," International Petroleum Technology Conference, Kuala Lumpur, Malaysia, Dec. 10–12.
[7] Rabenjafimanantsoa, A. H., Time, R. W., and Saasen, A., 2005, "Flow Regimes Over Particle Beds, Experimental Studies of Particle Transport in Horizontal Pipes," 14th Annual Conference of the Nordic Rheology Society, Tampere, Finland, August, Ann. Trans. Nordic Rheology Soc., pp. 171–176.
[8] Pedrosa, C., Saasen, A., Lund, B., and Ytrehus, J. D., 2021, "Wet Drilled Cuttings Bed Rheology," Energies, **14**(6), p. 1644.
[9] Pedrosa, C., Ytrehus, J. D., Aschl, T., Lund, B., and Saasen, A., 2021, "Wet-Granular Rheology to Measure Cuttings-Bed Strength," Ann. Trans. Nordic Rheol. Soc., **29**, pp. 109–114.
[10] Maruzewski, P., Hasmatuchi, V., Mombelli, H. P., Burggraeve, D., Iosfin, J., Finnegan, P., and Avellan, F., 2009, "Surface Roughness Impact on Francis Turbine Performances and Prediction of Efficiency Step Up," Int. J. Fluid Mach. Syst., **2**(4), pp. 353–362.
[11] Huque, M., Rahman, M., Zendehboudi, S., Butt, S., and Imtiaz, S., 2022, "Experimental and Numerical Study of Cuttings Transport in Inclined Drilling Operations," J. Pet. Sci. Eng., **208**, p. 109394.
[12] Sayindla, S., Lund, B., Ytrehus, J. D., and Saasen, A., 2017, "Hole-Cleaning Performance Comparison of Oil-Based and Water-Based Drilling Fluids," J. Pet. Sci. Eng., **159**, pp. 49–57.