Review

Fundamentals and Physical Principles for Drilled Cuttings Transport—Cuttings Bed Sedimentation and Erosion

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Abstract: The increasing necessity of challenging wellbore structures and drilling optimization for improved hole cuttings cleaning has been growing along time. As a result, operator companies have been researching and applying different hole cleaning techniques. Some of these are applied as traditional rules of thumb but are not always suitable for the new and up-coming challenges. This may result in inefficient hole cleaning, non-productive times, pipe stocking and low rate of penetration (ROP), among other problems. Here are presented some results and improvements for hole cleaning optimization obtained by the different research groups. The different authors mainly focus on specific cuttings transport parameters and sometimes combination of some of them. For this reason, there has not been a study that takes into account all of the different factors at the same time to accurately predict the cuttings bed height, formation and erosion, critical fluid velocity and properties and other key parameters. Consequently, there is a lack of understanding about the relation between different factors, such as the cohesiveness of the drilled cuttings with the different interstitial drilling fluids within the cuttings-bed. This relation can be analyzed establishing a wet-granular approach to obtain more efficient cuttings transport mechanism in challenging conditions.

Keywords: cuttings removal; hole cleaning; drilling fluids

1. Introduction

Drilled cuttings are rock debris formed by the drill-bit shearing torque against the rock formation or by applying a crushing force acting vertically in the wellbore during drilling operations. These produced drilled cuttings must be transported out of the well by circulating drilling fluids from surface to the bottom-hole through the drill pipe and then from the bottom-hole to the surface through the annulus. Poor hole cuttings cleaning generates operational risks, such as increased filter cake thickness, pipe sticking, hole pack-off, higher drag and torque, low rate of penetration (ROP), or high annular circulating pressure [1]. All these problematics are provoking non-productive time and elevated operational costs. Additionally, difficulties in other operations such as casing running, cementing and wireline logging operations might also increase [2]. For this reason, understanding of hole cleaning efficiency is of utmost importance to successfully tailor high-performance drilling fluids to effectively lift and carry out the cuttings in accordance with the conditions during drilling and thereby lower the non-productive time.

Cuttings transport in vertical, deviated and horizontal wells have been studied since early 1980's. While drilling a vertical well, the hole cleaning process is easier and does not represent complex challenges due to the small area for cuttings accumulation and the fact that the drilling fluid flows in opposite direction to gravity. Hence, cuttings transportation can be controlled by high viscosity and ensuring good gel formation [3].

During directional drilling, effective drilling cuttings removal becomes more challenging. Due to the presence of large areas for cuttings accumulation and bed developing at the non-vertical sections, the solutions for vertical wells are not completely suitable for larger wellbore inclination angles. As directional and long horizontal sections in the exploration and development wells in the oil and gas industry are increasing, due to higher drainage areas, researchers are being forced to pay more attention to cuttings transport and hole cleaning. These subjects are been recognized as the most common problem in the deviated and horizontal sections of wells since directional drilling started [1].

Despite many years of research, both at academic and industrial level, effective hole cleaning still represents a major problematic issue in most highly deviated and horizontal wells [4]. Therefore, implementation of a combination of optimum drilling fluids designs, drilling program and fluid flow rate for directional drilling is a real challenge.

Hole cleaning is known to be different in cases of using oil-based or water-based drilling fluids [5]. The industry perception is that hole cleaning is easier with oil-based drilling fluid than with water-based [6]. This may be a result of different cuttings bed properties [5] or presence of normal stress differences working onto the bed because of the viscoelastic properties of water-based drilling fluids [7].

The purpose of the current paper is to describe the key factors that influence the drilling cuttings transportation and removal for improved hole cleaning efficiency. Some of these key factors are the cuttings settling velocity, the cuttings-bed formation and erosion. A connection to formation and handling of wet granular media is established. Due to its importance to proficiently address technically the operational challenges regarding cuttings removal and cleaning efficiency.

2. Key Factors in Drill Cuttings Transport

The key factors acknowledged to have an impact on cuttings removal, can be divided in three main groups [8]: (i) Operational factors, such as hole inclination, annular-eccentricity, drill-pipe rotation and fluid flow rate; (ii) drilling fluid parameters, such as rheological parameters, density and composition, and (iii) cuttings parameters, such as size, shape and type. Regardless of the understanding of the effect of these several factors, only a few of them can be effectively controlled during drilling for hole cleaning purposes. These three groups will be described, including the different approaches that have been given by different research groups.

2.1. Operational Factors

The operational factor group comprehends the factors associated with the drilling operation. Some of these can be controlled to achieve the required hole cleaning performance, but others should be left undisturbed as they are specific parameters of other drilling challenges. The following effects which fall under this category have been studied by several authors [9]; hole inclination, annular-eccentricity, drill-pipe rotation [10] and fluid flow rate and ROP.

In deviated wells, inclination can vary from vertical, to small angle changes, to horizontal. Hole inclination is a factor that cannot be modified to improve hole cleaning efficiency during drilling, as it is decided during the well-planning, according to the reservoir lithology and the desired trajectory. Similarly to the Boycott settling phenomena described in 1920 [11], which showed that blood corpuscles settle faster in inclined test tubes than in vertical ones; the drilled cuttings tend to settle faster in inclined trajectories. Among the different researchers, the common results showed that between 45° and 60° is the most critical angle for cuttings lifting and transport [12–16]. Nevertheless, the critical angle can swift between 60° and 90° depending on the drilling fluid type, flow rate [17] and the drill-pipe rotation and practical setup, as well as the conditions used for research.

Annular-eccentricity is a very difficult parameter to control, as it is the result of the hole inclination, drill-pipe movement and weight on bit. When eccentricity is non-zero, or the standoff is less than unity, the drill-pipe is close to the hole wall, creating two different

paths, a wider path with no drill-pipe and a more restrict path where the drill-pipe is located. In this narrow part of the annulus, the fluid flow velocity is low, triggering the cuttings-bed buildup depending on the pipe rotation [1]. Thus, eccentricity is making pipe rotation a significant factor for hole cleaning [18]. In the case of no pipe rotation, the fluid flow on the restricted narrow path is not sufficient to prevent bed formation nor to provoke cuttings movement. On the other hand, when pipe rotation is applied, the cuttings-bed is broken due to either Taylor forces created by the flow caused by the pipe movement or simply by direct friction forces, and the drilled cuttings will be effectively lifted to the wider path [19] where the rapid fluid flow will carry them further. This may prevent bed formation and improve hole cleaning efficiency [20]. Thus hole cleaning efficiency relies on non-controllable annular eccentricities to remove cuttings or prevent bed formation [3].

Drill-pipe rotation is a factor that cannot generally be modified as it is needed to control cuttings removal. During drilling, rotation is not always possible to adjust according to single parameters as it depends on many factors during the drilling process, including lithology, trajectory and desired ROP. The overall findings conclude that pipe rotation significantly enhances hole cleaning efficiency, being responsible for the greatest effect of hole cleaning when small cuttings are present [8,14,21–23]. Rotational speed enhances hole cleaning efficiency largely up to certain range, although at higher rotations typically above 100 RPM in laboratory cases, there is not much contribution to hole cleaning, as hole cleaning often is close to 100% [24,25].

When no rotation is present, it is very important to carefully chose the type of drilling fluid, to overcome the lack of mechanic aid to remove cuttings. As has been described by Sayindla et al. [6], oil-based drilling fluids provide better hole cleaning properties than water-based fluids when they have similar rheological responses, as per API specifications [26].

Fluid flow rate and fluid rheological parameters are parameters that largely influence cuttings transport and are relatively easy to control during drilling operations. The fluid flow rate can facilitate hole cleaning process depending on the inclination and type of flow. In horizontal and near horizontal wells the use of turbulent flows is recommendable as the shear stress that is applied to the cuttings-bed is higher [3]. For vertical and near vertical wells, as the cuttings fall opposite to the flow direction, it is recommended to work with laminar flows [27], to prevent particles to move downwards so easily. As horizontal wells normally also have a vertical section, this shows one of the difficulties in maintaining overall good hole cleaning.

Modifying the drilling fluid flow at any rate may not be sufficient to satisfactorily disturb the deposited cuttings-bed. It is of utmost importance to reach, and if possible, exceed a critical flow rate and shear stress threshold for bed erosion [4,28]. Sometimes it is not possible to reach the ideally high flow rates due to borehole instability problems and limited surface equipment capabilities. Martins [29] developed correlations to determine the critical shear stress required to remove cuttings, by using a complex dimensionless friction factor that depends on the Reynolds number, the fluid behavior index and the particle diameter ratio.

The flow regime was shown to have an impact on cuttings transport, it has been demonstrated that at angles from $0°$ to $45°$, it is preferable to have a laminar flow and at angles near to horizontal it is preferable to have turbulent flows [30]. The flow regime can be calculated using the Reynolds number defined by Founargiotakis [31] shown in Equation (3) for a Hershel-Bulkley fluid in a concentric annulus. Guillot [32] noted that there is not a single transition flow point, but a transition region, which is defined by the following equations:

$$Re_1 = 3250 - 1150(n') \tag{1}$$

$$Re_2 = 4150 - 1150(n') \tag{2}$$

where Re_1 denotes the Reynolds number at beginning of the transition region and Re_2 denotes the Reynolds number at the end of the region, K' is the local consistency index and n' being the local flow index when describing the flow with a power-law fluid.

$$Re = \frac{\rho V^{2-n'}(d_2 - d_1)^{n'}}{K'(12)^{n'-1}} \tag{3}$$

The fluid flow rate can be expressed in terms of shear rate for a laminar flow in a concentric annulus with drill string rotation according to the narrow slot approximation described by Saasen [33] This is represented in Equation (4):

$$\dot{\gamma} = \left[\left(\frac{12U}{(d_o - d_i)} \frac{2n'+1}{3n'} \right)^2 + \left(\frac{\omega d_i}{(d_o - d_i)} \right)^2 \right]^{1/2} \tag{4}$$

where; d_o is the open hole diameter and d_i is the diameter of the drill pipe. The flow type as described above is dependent on some rheological values that are specific for each fluid, such as, the local flow index or curvature exponent (n') at a specific angular velocity (ω) and bulk axial velocity (U), thus the drilling fluid parameters need to be taken into consideration.

In addition to a flow type according to the Reynolds number, as drill-pipe rotation is normally present, it is important to consider the inertial forces due to rotation and viscous forces, better known as Taylor number (Ta). The Taylor number is described in Equation (5). When axial motion is present full turbulence is expected in a well when Taylor number exceeds 2×10^6 [34].

$$Ta = \frac{\omega^2 d_i^4 \rho^2}{4\eta^2} \frac{\lambda^2}{1-\lambda^2} \left(\frac{1-\lambda}{\lambda} \right)^4 \tag{5}$$

where λ is the corresponding diameter ratio between the inner and outer cylinder, or drill pipe and hole diameters, (d_i/d_o).

Another operational factor that should be taken into account and optimized during the drilling plan is the rate of penetration (ROP). It is beneficial to drill near the optimal ROP or below, as it has been shown [35] that when drilling at elevated ROP the effective hole cleaning capabilities can be exceeded. Several side-effects could then occur. Cleaning efficiency problems may originate from this; one of them is the size of the cuttings and cavings. This can give larger particles, as the contact time with the drill-bit is not enough to shape it down. Cuttings accumulation can then become higher and lead to increased equivalent circulating density (ECD). As consequence of increased ECD it can be necessary to reduce flow rates that eventually may cause faster cuttings accumulation.

2.2. Drilling Fluid Parameters

Drilling fluids are used in the oil and gas industry for every drilling operation. Such fluids have many functions. These includes balance pressure in the wellbore, control formation pressures, lubricate and cool down the drill-bit and finally carry out drilling cuttings and suspend them while drilling is paused [36]. To achieve these challenges several fluid properties must be considered, such as rheological parameters, density and chemical composition.

The drilling industry uses long-established standard procedures for characterizing the fluidity and viscosity of drilling fluids. The Marsh funnel measurement system [37] was established already in 1931, providing a simple, reliable and repeatable measure of fluid viscosity. The Marsh funnel design is still utilized on drilling rigs for simple continuous monitoring of drilling fluid rheology, enabling immediate adjustment of fluid composition. However, the funnel viscosity is merely a measure of elongational viscosities than shear dependent viscosities. For more complex rheological characterization of drilling fluids, API-13B recommended practice has been established based on the Bingham model [38], designating a strain-invariant yield stress threshold and concomitant plastic viscosity term.

In practice, Bingham parameters are derived from torque measurements obtained at 300 rpm and 600 rpm in a rotational model 35 viscometer. In the last decades, it has been recognized that use of this model may introduce large errors [39].

The non-linear Herschel-Bulkley model was incorporated into industrial calculations for drilling fluid rheology, to describe the fluid's flow curve with reasonable accuracy, encompassing the shear deformation spectrum ranging from 5.11 s^{-1} to 1022 s^{-1}, obtaining a dynamic yield stress by extrapolation. In addition, there are more advanced rheological models which also incorporate thixotropic effects [40].

In the Herschel-Bulkley model the shear stress σ, is related to a dynamic yield stress (σ_y), a consistency factor (K), the curvature exponent (n), and the shear rate ($\dot{y}$) (velocity gradient) as described in the constitutive Equation (6):

$$\sigma = \sigma_y + K\dot{y}^n \tag{6}$$

Although this is a more accurate model over a large range of shear rates, its parameters K and n alone should not be used for direct comparison, but instead the complete flow curve [41,42].

Understanding of the fluid rheological behavior is very important as this might affect the cuttings slip velocity in horizontal, deviated or vertical configurations. It has been demonstrated [43–45] that high viscosities tend to improve the cleaning efficiency in vertical and near-to vertical wells. Here the cuttings movement is almost against to the flow direction. The cuttings sedimentation tends to undergo retardation due to high viscosity when circulation is paused. When flow is resumed the particles are transported out by flow rate [46]. In highly deviated or horizontal wells, there is less or no benefit of having high viscosity as the increased viscosity reduces greatly the slipping rate, in absence of drill string rotation. Therefore, it is recommendable to use low viscosity fluids, in addition to relatively high flow rates, at highly deviated and horizontal wells to induce non-laminar or turbulent annular flow.

A study of oil-based drilling fluids with similar densities, all constructed for highly deviated drilling, was performed by Ytrehus et al. [47]. The study demonstrates cuttings transport efficiency as function of ECD at various inclinations. Bizhani and Kuru [7] showed that the lift forces are much smaller than the drag forces, which helps to explain the reason why it is harder to remove cuttings which have already been embedded in a cuttings-bed. Adari et al. [3] supported this through studying how the cuttings bed height is lower when n/K ratios are higher.

Not only fluid flow behavior and viscosity influence cleaning efficiency, but also its yield stress and thixotropy [48–50] will increase or impede cuttings suspension and transport efficiency out of the well. The drilling fluid yield stress value affects greatly the cuttings deposition velocity, thus preventing the cuttings particles to settle down forming a bed.

The composition of drilling fluid is another factor that is being studied, as it is not fully understood the reasons why oil-based fluids (OBM) and water-based fluids (WBM) behave differently in terms of cuttings transport and cleaning efficiency, even when the viscosity profiles and densities are similar [5,35,51]. This is an important matter briefly discussed by [6], but not explained properly. Nevertheless, it is considered as good industry practice, and it has been shown, that OBM have superior hole cleaning performance in highly deviated and horizontal well configurations. For cases of high drill-pipe rotation rates the differences in hole cleaning efficiency between the results of using WBM or OBM are less than without rotation [6].

2.3. Cuttings Parameters

The dynamic behavior of the drilling cuttings in the flowing media is governed by the size, specific gravity, shape and weight; the specific gravity of the vast majority of the drilled formations is on average 2.6. The cuttings can be assumed as known, but the size, shape and weight of the cuttings depend on several factors, such as lithology, drill-bit type,

weight on bit, regrinding by the bottom-hole-assembly, rate of penetration, among others. This makes it impossible to assume average or uniform size and shape of the drilling cuttings [45].

During actual drilling operations the drilled cuttings from different sections have been measured to vary from more than 8 mm down to less than 0.045 mm [52]. The particle size distribution does not have a constant tendency across the different hole diameters or lithology. The only parameter that can be controlled is the cuttings concentration in the wellbore as calculated in terms of ROP. Field thumb rule states that if more cuttings are produced, higher flow rate should be applied to prevent cuttings-bed formation.

The size and shape of the cuttings have complicated effects on the hole cleaning efficiency [53]. In general, the quantity of smaller particles is higher than larger particles in highly deviated wellbores, between 70–90°, on the contrary the number of larger particles in wellbores between 0–60° is higher than smaller particles. Consequently, several authors have studied the cutting size importance. In Table 1, it is possible to observe the evolving studies across time.

Table 1. Cuttings size study development along time.

Authors	Particle Size	Conclusions
Peden et al. [13] 1990	1.7–2.0 mm 2.8–3.5 mm	Cleaning efficiency is higher for small cuttings when using low viscosity fluids at any angle, and for larger particles, high viscosity fluids show better results between 0–50°
Martins et al. [54] 1996	2.1 mm and 4.2 mm	Cuttings bed with larger particles are more difficult to erode using water viscosified by xanthan gum as the fluid.
Sanchez et al. [22] 1999	2.5 mm and 6.3 mm	Inclination does not modify cuttings size behavior for hole cleaning efficiency.
Walker and Li [27] 2000	0.5–7mm	Smaller particles are easier to remove. The most difficult particles to remove are spherical particles with average size of 0.76 mm.
Duan et al. [21] 2008	0.45, 1.4 and 3.3 mm	Smaller particles are easier to remove when using viscosified fluids, in comparison to pure water where smaller particles are more difficult to remove.
Zhu et al. [55] 2019	1, 2, 3, 4 and 5 mm	Small cuttings reduce the bed height and show higher transport speed
Hirpa et al. [56] 2020	149–841 μm	With water as the displacement fluid, when particle size increases the critical flow rate required to initiate particles movement in the bed also increases.

As an evolving knowledge, cutting size has complicated effects, and depends on other parameters, such as the fluid type used, the viscosity of the same, well inclination, and fluid velocity, nevertheless, all authors seem to agree that when using water based drilling fluid, particles with size less than 0.8mm are easier to remove.

3. Cuttings Settling Velocity and Erosion

To obtain a better understanding on the cleaning efficiency it is important to understand the cuttings-bed build-up process, which is mainly focused on the cuttings settling or slip velocity, which is the velocity at which the cuttings particles precipitate due to gravity forces, along the cross-sectional area of the wellbore. Several authors [3,4,57–59] have studied this process, concluding that the critical flow velocity is the minimal fluid velocity needed to overcome gravitational, contact and bonding forces. This minimal velocity must still maintain a continuously upward movement of all cuttings in the annulus during drilling operations. To maintain this critical flow velocity during drilling operations is highly difficult, making it important to accurately calculate the settling velocity [60]. Then it may be possible to estimate the cuttings concentration profile and control the pressure downhole. Along time, several authors have developed correlations to describe the settling behavior, although a completely accurate equation has not yet been developed, because many factors are known to affect the settling velocity, such as cuttings shape, size and density, drilling fluid rheological parameters, density and velocity, wellbore inclination and pipe rotation.

The most common approaches to correlate settling velocity began with Concha and Almendra in 1979 [61] by calculating the drag coefficient in a specific drilling fluid [62]. Later a more complex two-layer model [63] and three-layer model [64] model were developed, and have been evolved along the time. In 1996 a set of correlations was developed

to predict more accurately the interfacial friction factor for highly inclined wellbores [29]. A study based on drilling fluid's yield stress response from the stress overshoot test, was used to improve the settling velocity prediction in 2015 [60]. In 2018 [7] lift and drag forces were analyzed. The study showed that drag forces in particle transport phenomena dominated over lift forces. Therefore, it is advisable to focus on the bed shear stress to describe bed-erosion. A very good review of the layer models and their variations is held by Kelessidis and Bandelis [65].

In the two-layer model, exists one layer of solid materials, which is the moving cuttings bed, and another of flowing fluid, which contains suspended solids, the governing equations [65] are divided into balance equations (for solids Equation (7), for liquids Equation (8), for mean concentration of solids in liquid Equation (9)), momentum equations (for solids Equation (10), for liquids Equation (11)) and finally closure equations as presented below:

$$U_s A_s C_s + U_B A_B C_B = U_M A_M C_M \tag{7}$$

$$U_s A_s (1 - C_s) + U_B A_B (1 - C_B) = U_M A_M (1 - C_M) \tag{8}$$

$$C_s = \frac{C_B}{2A_s} \left(d_o^2 * I_o - d_i^2 * I_i \right) \tag{9}$$

$$A_s \frac{\mathrm{d}p}{\mathrm{d}z} = -\sigma_s S_s - \sigma_i S_i \tag{10}$$

$$A_B \frac{\mathrm{d}p}{\mathrm{d}z} = -F_B - \tau_B S_B + \sigma_i S_i \tag{11}$$

where U_s is the mean velocity of the suspension, U_B is the mean velocity of the bed and U_M is the mean velocity of the mixture. A_s is the cross-sectional area occupied by the suspension layer, A_B is the cross-sectional area occupied by the bed layer and A_M is the cross-sectional area of the annulus. C_s is the mean concentration of solid in the suspension layer, C_B is the mean concentration of solid in the bed layer and C_M is the mean feed concentration.

There are 5 unknowns and 5 equations, but to solve them it is necessary to have closure relationships for the shear stress (σ), the friction force (F), the particle-settling velocity (u_p) and the dispersion coefficient of the solids (D), which are fully described by Kelessidis and Bandelis [65].

In the three-layer model, the lower layer represents the cuttings-bed, the middle one is a dispersed layer in which particles concentration varies, and a final layer of a flowing fluid, momentum equations are used for each layer and several closure relationships which need to be solved simultaneously, thus computer software is fundamental to perform the calculations. The governing equations for this model are:

$$U_s A_s C_s + U_{mB} A_{mB} C_{mB} = U_M A_M C_M \tag{12}$$

$$U_s A_s (1 - C_s) + U_{mB} A_{mB} (1 - C_{mB}) = U_M A_M (1 - C_M) \tag{13}$$

where U_{mB} is is the moving bed velocity, A_{mB} is the cross-sectional area of the moving bed and C_{mB} is the mean concentration of solids in moving bed.

These two equations, (12) and (13) correspond to the mass balances for the solid and for the liquid respectively, the momentum equations, describe the suspended layer in Equation (14), the moving bed layer in Equation (15) and the stationary bed layer in Equation (16).

$$A_s \frac{\mathrm{d}p}{\mathrm{d}z} = -\sigma_s S_s - \sigma_{smB} S_{smB} \tag{14}$$

$$A_{mB} \frac{\mathrm{d}p}{\mathrm{d}z} = -F_{mBsB} - F_{mB} - \sigma_{mBsB} S_{mBsB} - \sigma_{mB} S_{mB} + \sigma_{smB} S_{smB} \tag{15}$$

$$A_{sB} \frac{\mathrm{d}p}{\mathrm{d}z} + F_{mBsB} + \sigma_{mBsB} S_{mBsB} \leq F_{sB} \tag{16}$$

where σ_s is the suspension shear stress, σ_{smB} is the suspension/moving bed shear stress, σ_{mBsB} is the moving bed/stationary bed shear stress, σ_{mB} is the moving bed shear stress. S_s is the wetted perimeter of the bed, S_{smB} is the wetted perimeter between suspension and moving bed, S_{mBsB} is the wetted perimeter between moving bed and stationary bed. F_{mBsB} is the friction force between the moving bed and the stationary bed, F_{mB} is the friction force between the moving bed and the wall, F_{sB} is the friction force between the stationary bed and the wall.

Similarly, to the two-layer model, it is necessary to use closure relationships to solve the unknowns, which include stresses, friction forces and diffusion, but also some authors use the turbulent-boundary-layer theory [64–66].

Effective erosion of the cuttings-bed has major influence on the cleaning efficiency, it has been demonstrated that loose and porous cuttings-beds are easier to clean as single cuttings particles can move freely into the bed, on the other hand, well consolidated cuttings-bed are more complex to clean as the cuttings particles are embedded into the bed and there are not loose particles to move [51]. It has been shown [21,27,55] that to disturb the cuttings at rest and erode the cuttings bed, it is necessary to reach the critical velocity, and it was discussed, that smaller cuttings particles are easier to erode from the cuttings bed.

Understanding of the acting forces on a cutting particle's motion is important in the analysis of bed erosion and hole cleaning efficiency. The interaction between the drilled cuttings particles and the drilling fluids play an important role to analyze the acting forces to start the motion of a particle in the cuttings bed that tends to settle down and remain embedded due to stabilization forces such as gravity, buoyancy and plasticity.

When the drilling fluid flows over a cuttings bed, different forces act to remove cuttings particles from the cuttings bed [67–69], such as:

Net weight force;

$$F_b = \frac{\pi}{6}d_p^3\left(\rho_s - \rho_f\right)g \tag{17}$$

Hydrodynamic drag force;

$$F_d = \frac{\pi}{8}C_D\rho_f U^2 d_p^2 \tag{18}$$

Adhesion-cohesion force;

$$F_{ac} = C_1 d_p \tag{19}$$

Updraft under a burst force;

$$F_c = \pi C_2 \rho_f U^2 r^{+3} \tag{20}$$

where these last two are addressed by other authors as:

Plastic force;

$$F_p = \frac{\pi}{4}d_p^2\sigma_y \tag{21}$$

Lift force;

$$F_l = \frac{\pi}{8}d_p^2 C_L \rho_f U^2 \tag{22}$$

where d_p is the particle diameter, C_D is the drag coefficient, U is the bulk axial velocity, C_1 is the adhesion coefficient, C_2 is the updraft under a burst coefficient.

Some of these forces are more dominant than others depending on the particle size. In the case of large particles (above 200 μm) the dominant forces are net weight and hydrodynamic drag. In the intermediate particle range (30–200 μm) the dominant forces are updraft under a burst and net weight. For the smaller particles (below 30 μm) adhesion-cohesion and updraft under a burst forces are the dominant ones [68].

Taking into account the acting forces previously described, the two main transport phenomena that provoke cuttings-bed erosion by initiating particles movement are lifting or saltation and dragging or rolling, where lifting is the phenomena that occurs when

flow velocity is higher than critical velocity to lift cuttings particles up, but not sufficient to hold these particles into suspension. Lifting was shown to have more importance at low deviation angles and dragging is the dominant force on high inclinations and horizontal wells. These phenomena have been discussed by several authors [57,58,70,71], and Ramadan et al. [69], summarizes and describes the importance of these mechanisms for deviated wells, focusing on their critical velocity, assuming that the cuttings are formed by spherical particles of uniform size, no flow fluctuation and uniform bed thickness. Equation (23) describes the critical velocity to lift a particle from the surface of the bed, which depends on the drilling fluid yield stress (σ_y), drilling fluid density(ρ_f), the fluid to solid density ratio (*s*), lifting coefficient (C_L), mean particle diameter (d_p), and inclination angle (α):

$$u_L = \left(\frac{2\sigma_y}{C_L \rho_f} + \frac{4d_p sin\alpha (s-1)g}{3C_L} \right)^{0.5} \tag{23}$$

Equation (24) describes drag critical velocity, which is the minimum velocity required to initiate particle movement by rolling in a thin layer along the cuttings-bed, the drag critical velocity depends on some parameters equal to the lifting critical velocity, nevertheless, in the drag it should be taken into account the angle at rest (φ), drag coefficient (C_D) and the drag ratio (D_R); usually the two critical velocities are different, thus the lower value must be considered as the critical value that dominates the transport phenomena:

$$u_R = \left(\frac{6\sigma_y \cos O + 4d_p g(s-1) \sin(O + \alpha)}{3(D_R C_D sinO + C_L \cos O)} \right)^{0.5} \tag{24}$$

With these equations and the experimental data, it was concluded that lifting phenomena is stronger at low angle of inclination and it reduces its force as the wellbore inclination increases, in the same way dragging gets more important at both intermediate and high deviated angles. Although it is important to note, that these model does not fit very well for vertical or near vertical wells, for those cases it is recommended to use the Kelvin–Helmholtz stability model.

As the most challenging cases for drilling cuttings transport are at highly deviated and horizontal wells, it would be very advantageous to perform experiments and studies that focus on studying the cohesion mechanism of the cutting particles, according to the different types of drilling fluid. It has been discussed that even while having similar rheological properties and densities, the OBM and WBM behave differently, this could be due to OBM are polymer-free fluids, meanwhile WBM are composed of several long-chain polymers, thus these chains can generate bonding forces to the embedded cuttings, forming more consolidated bed [5].

To study the internal cohesiveness of the cuttings bed, it is necessary to understand the bonding forces between particles submerged in an interstitial fluid. Some authors are considering the development of granular and wet-granular rheological characterization [72–75] of the beds. This could help understanding the governing principle of cuttings dragging in a cuttings-bed. This approach has not yet been applied to drilled cuttings wetted by a real drilling fluid. However, this theory can give an understanding on how the different drilling fluids and cutting types can influence the drilling cuttings transport phenomena and, thus, hole cleaning in general. Wet-granular rheology identifies the cohesion and internal friction between particles in a dense particle agglomeration. This understanding should help to quantify the necessary dragging force in terms of interfacial forces between the cutting-bed particles. Hopefully, such analysis will explain whether usage of a water-based or oil-based drilling fluid should generate higher particle cohesion, when the fluids are having similar viscous properties.

4. Conclusions and Recommendations

Different approaches and studies on specific conditions by different research groups have been reviewed in this article. The focus has been on the main factors that influence

the drilling cuttings transport phenomena, including operational factors, drilling fluid parameters and cuttings parameters.

An evolution of the hole cleaning concepts, and more realistic experimental setups and experiments is shown. Most authors experienced the same results, such as the most critical angle of well inclination for cuttings transport being 60°, although some got different results and the critical angle can vary within a range from 45° to 90°. One parameter which the different authors have been obtaining different results is the efficiency according the type of drilling fluid, making unclear which type of drilling fluid is more recommendable to improve the hole cleaning efficiency. The reason for different results could be because of testing the same parameters but at different conditions affecting the overall results.

The main results state:

- Opposite to what is recommended in vertical wells, high drilling fluid viscosities are not recommended for highly deviated wells.
- There are three main factors that affect the cuttings removal, which are the operational parameters, the fluid properties and the cuttings properties.
- The most critical inclination angle for cuttings cleaning has been found to occur between 45° and 60°.
- Annular eccentricity is a very difficult parameter to control in the wellbore, so hole cleaning shall not rely on an efficient control of this parameter.
- ROP should be increased at the maximum possible but ensuring not to exceed the point where the efficiency level of hole cleaning cannot be reached.
- Use of oil-based and water-based drilling fluids are found to provide different degree of hole cleaning even if their viscous properties are similar.

Hole cleaning cannot be predicted by a single parameter or factor by itself, it must be linked with all the different factors present at each specific drilling condition as some properties can have contradictory results depending on other fluids, cuttings or operational factors.

In horizontal and highly inclined wellbores, the main forces that lead the bed-erosion, thus are the dominating forces for cuttings-transport are drag forces, while for near to vertical wellbores are the lifting or saltation forces.

It is important to develop accurate predictive correlations for water-based and oil-based drilling fluids dragging forces. To be able to tailor the drilling fluid for each wellbore section, this can be done through using wet-granular rheology to determine the cohesive forces in cuttings beds for each type of drilling fluid as an interstitial fluid.

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References

1. Tomren, P.; Iyoho, A.; Azar, J. Experimental Study of Cuttings Transport in Directional Wells. *SPE Drill. Eng.* **1986**, *1*, 43–56. [CrossRef]
2. Bizhani, M.; Corredor, F.E.R.; Kuru, E. Quantitative Evaluation of Critical Conditions Required for Effective Hole Cleaning in Coiled-Tubing Drilling of Horizontal Wells. *SPE Drill. Complet.* **2016**, *31*, 188–199. [CrossRef]
3. Adari, R.B.; Miska, S.; Kuru, E.; Bern, P.; Saasen, A. Selecting Drilling Fluid Properties and Flow Rates For Effective Hole Cleaning in High-Angle and Horizontal Wells. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 1–4 October 2000.

4. Li, J.; Luft, B. Overview of Solids Transport Study and Application in Oil-Gas Industry-Theoretical Work. In Proceedings of the SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition, Moscow, Russia, 14–16 October 2014.

5. Saasen, A. Hole Cleaning During Deviated Drilling—The Effects of Pump Rate and Rheology. In Proceedings of the European Petroleum Conference, The Hague, The Netherlands, 20–22 October 1998.

6. Sayindla, S.; Lund, B.; Ytrehus, J.D.; Saasen, A. Hole-cleaning performance comparison of oil-based and watr-based drilling fluids. *J. Pet. Sci. Eng.* **2017**, *159*, 49–57. [CrossRef]

7. Bizhani, M.; Kuru, E. Critical Review of Mechanistic and Empirical (Semimechanistic) Models for Particle Removal From Sandbed Deposits in Horizontal Annuli With Water. *SPE J.* **2018**, *23*, 237–255. [CrossRef]

8. Bilgesu, H.I.; Mishra, N.; Ameri, S. Understanding the Effects of Drilling Parameters on Hole Cleaning in Horizontal and Deviated Wellbores Using Computational Fluid Dynamics. In Proceedings of the Eastern Regional Meeting, Lexington, KY, USA, 4–6 October 2017.

9. Nazari, T.; Hareland, G.; Azar, J.J. Review of cuttings transport in directional well drilling: Systematic approach. In Proceedings of the SPE Western Regional Meeting, Anaheim, CA, USA, 27–29 May 2010; p. 15.

10. Ytrehus, J.D.; Taghipour, A.; Lund, B.; Werner, B.; Opedal, N.; Saasen, A.; Ibragimova, Z. Experimental Study of Cuttings Transport Efficiency of Water Based Drilling Fluids. In Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, CA, USA, 8–13 June 2014.

11. Boycott, A.E. Sedimentation of Blood Corpuscles. *Nature* **1920**, *104*, 532. [CrossRef]

12. Katende, A.; Segar, B.; Ismail, I.; Sagala, F.; Saadiah, H.H.A.R.; Samsuri, A. The efect of drill–pipe rotation on improving hole cleaning using polypropylene beads in water-based mud at diferent hole angles. *J. Pet. Explor. Prod. Technol.* **2020**, *10*, 1253–1262. [CrossRef]

13. Peden, J.; Ford, J.; Oyeneyin, M. Comprehensive experimental investigation of drilled cuttings transport in inclined wells including the efects of rotation and eccentricity. In Proceedings of the European Petroleum Conference, The Hague, Netherlands, 21–24 October 1990.

14. Sifferman, T.R.; Becker, T.R. Hole cleaning in full-scale inclined wellbores. *SPE Drill. Eng.* **1992**, *7*, 115–120. [CrossRef]

15. Ytrehus, J.D.; Lund, B.; Taghipour, M.A.; Kosberg, B.R.; Carazza, L.; Gyland, K.R.; Saasen, A. Hydraulic Behavior in Cased and Open-Hole Sections in Highly Deviated Wellbores. *J. Energy Resour. Technol.* **2021**, *143*, 1–8. [CrossRef]

16. Li, J.; Walker, S. Sensitivity Analysis of Hole Cleaning Parameters in Directional Wells. *SPE J.* **2001**, *6*, 356–363. [CrossRef]

17. Hemphill, T.; Larsen, T.I. Hole-Cleaning Capabilities of Oil-Based and Water-Based Drilling Fluids: A Comparative Experimental Study. In Proceedings of the 68th SPE Annual Technical Conference and Exhibition, Denver, CO, USA, 6–9 October 1996.

18. Ahmed, R.M.; Enfis, M.S.; El Kheir, H.M.; Laget, M.; Saasen, A. The Effect of Drillstring Rotation on Equivalent Circulation Density: Modeling and Analysis of Field Measurements. In Proceedings of theSPE Annual Technical Conference and Exhibition, Florence, Italy, 20–22 September 2010.

19. Escudier, M.; Gouldson, I.; Oliveira, P.J.; Pinho, F.T. Effects of inner cylinder rotation on laminar flow of a Newtonian fluid through an eccentric annulus. *Int. J. Heat Fluid Flow* **2000**, *21*, 92–103. [CrossRef]

20. Hemphill, T.; Ravi, K. Pipe rotation and hole cleaning in an eccentric annulus. In Proceedings of the IADC/SPE Drilling Conference, Miami, FL, USA, 21–23 February 2006.

21. Duan, M.; Miska, S.Z.; Yu, M.; Takach, N.; Ahmed, R.; Zettner, C.M. Transport of Small Cuttings in Extended-Reach Drilling. *SPE Drill. Complet.* **2008**, *23*, 258–265. [CrossRef]

22. Sanchez, R.A.; Azar, J.; Bassal, A.; Martins, A. Effect of Drillpipe Rotation on Hole Cleaning During Directional-Well Drilling. *SPE J.* **1999**, *4*, 101–108. [CrossRef]

23. Nguyen, T.M.; Yu, M.; Takach, N.; Ahmed, R.; Saasen, A.; Omland, T.; Maxey, J. Experimental study of dynamic barite sag in oil-based drilling fluids using a modified rotational viscometer and a flow loop. *J. Pet. Sci. Eng.* **2011**, *78*, 160–165. [CrossRef]

24. Sayindla, S.; Lund, B.; Taghipour, A.; Werner, B.; Saasen, A.; Gyland, K.R.; Ibragimova, Z.; Ytrehus, J.D. Experimental Investigation of Cuttings Transport with Oil Based Drilling Fluids. In Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering, Busan, Korea, 18–24 June 2016.

25. Ozbayoglu, M.E.; Saasen, A.; Sorgun, M.; Svanes, K. Effect of Pipe Rotation on Hole Cleaning for Water-Based Drilling Fluids in Horizontal and Deviated Wells. In Proceedings of the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Jakarta, Indonesia, 25–27 August 2008.

26. API. ANSI/API Recommended Practice 13B-1. In *Recommended Practice for Field Testing Water-based Drilling Fluids*; API: Washington, DC, USA, 2009.

27. Walker, S.; Li, J. The Effects of Particle Size, Fluid Rheology, and Pipe Eccentricity on Cuttings Transport. In Proceedings of the SPE/ICoTA Coiled Tubing Roundtable, Houston, TX, USA, 5–6 April 2000.

28. Li, J.; Luft, B. Overview of solids transport studies and applications in oil and gas indutry—Experimental work. In Proceedings of the SPE Russian Oil & Gas Exploration & Production Technical Conference and Exhibition, Moscow, Russia, 14–16 October 2014.

29. Martins, A.L.; Sa, C.H.M.; Lourenco, A.M.F.; Freire, L.G.M.; Campos, W. Experimental Determination of Interfacial Friction Factor in Horizontal Drilling with a Bed of Cuttings. In Proceedings of the SPE Latin America/Caribbean Petroleum Engineering Conference, Port of Spain, Trinidad, 23–26 April 1996.

30. Becker, T.; Azar, J.; Okrajni, S. Correlations of Mud Rheological Properties With Cuttings-Transport Performance in Directional Drilling. *SPE Drill. Eng.* **1991**, *6*, 16–24. [CrossRef]

31. Founargiotakis, K.; Kelessidis, V.C.; Maglione, R. Laminar, transitional and turbulent flow of Herschel-Bulkley fluids in concentric annulus. *Can. J. Chem. Eng.* **2008**, *86*, 676–683. [CrossRef]
32. Nelson, E.; Guillot, D. *Well-Cementing*; Schlumberger: Houston, TX, USA, 2006.
33. Saasen, A. Annular Frictional Pressure Losses During Drilling: The Effect of Drillstring Rotation. In Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering, Nantes, France, 9–14 June 2013.
34. Saasen, A. Annular Frictional Pressure Losses During Drilling—Predicting the Effect of Drillstring Rotation. *J. Energy Resour. Technol.* **2014**, *136*, 034501. [CrossRef]
35. Aldea, C.A.; Iyoho, W.; Zamora, M. *Hole Cleaning: The Achilles' Heel of Drilling Performance*; American Association of Drilling Engineers: Houston, TX, USA, 2005.
36. Mitchell, R.F. *Petroleum Engineering Handbook Volume II Drilling Engineering*; Society of Petroleum Engineers: Richardson, TX, USA, 2006.
37. Marsh, H.N. Properties and Treatment of Rotary Mud. *Trans. AIME* **1931**, *92*, 234–251. [CrossRef]
38. Frigaard, I.; Paso, K.; Mendes, P. Bingham's model in the oil and gas industry. *Rheol. Acta* **2017**, *56*, 259–282. [CrossRef]
39. Skadsem, H.J.; Leulseged, A.; Asoodeh, S. Measurement of Drilling Fluid Rheology and Modeling of Thixotropic Behavior. *Appl. Rheol.* **2019**, *29*, 1–11. [CrossRef]
40. Mendes, P.R.D.S.; Thompson, R.L. A unified approach to model elasto-viscoplastic thixotropic yield-stress materials and apparent yield-stress fluids. *Rheol. Acta* **2013**, *52*, 673–694. [CrossRef]
41. Saasen, A.; Ytrehus, J.D. Viscosity Models for Drilling Fluids—Herschel-Bulkley Parameters and Their Use. *Energies* **2020**, *13*, 5271. [CrossRef]
42. Saasen, A.; Ytrehus, J.D. Rheological Properties of Drilling Fluids: Use of Dimensionless Shear Rates in Herschel-Bulkley and Power-law Models. *Appl. Rheol.* **2018**, *28*, 54515.
43. Hopkin, E. Factors Affecting Cuttings Removal During Rotary Drilling. *J. Pet. Technol.* **1967**, *19*, 807–814. [CrossRef]
44. Ismail, A.R.; Hassan, Z.; Mazen, A.M. Drilling fluids and wellbore cleaning technology. In Proceedings of the Regional Symposium of Chemical Engineering, Petaling Jaya, Malaysia, 28–30 October 2002.
45. Azar, J.; Sanchez, A. Important issues in cuttings transport for drilling directional wells. In Proceedings of the Latin American and Caribbean Petroleum Engineering Conference, Rio de Janeiro, Brazil, 30 August–3 September 1997.
46. Cho, H.; Subhash, N.; Osisanya, S. Selection of optimum Coiled-tubing drilling parameters through the cuttings-bed characterization. In Proceedings of the SPE/ICoTA, Houston, TX, USA, 7–8 March 2001.
47. Ytrehus, J.D.; Lund, B.; Taghipour, A.; Carazza, L.; Gyland, K.R.; Saasen, A. Drilling fluids cuttings bed removal properties for deviated wellbores. In Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering, Fort Lauderdale, FL, USA, 3–7 August 2020.
48. Moller, P.; Fall, A.; Chikkadi, V.; Derks, D.; Bonn, D. An attempt to categorize yield stress fluid behaviour. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2009**, *367*, 5139–5155. [CrossRef]
49. Jachnik, R. Drilling fluid thixotropy and relevance. *Annu. Trans. Nord. Rheol. Soc.* **2005**, *13*, 1–6.
50. Pedrosa, C.; Ofei, T.N.; Purwandari, S.D.; Lund, B.; Paso, K.G. Cellulose nanofibers facilitate heavy particle suspension in drilling fluids. In Proceedings of the Nordic Rheology Conference, Online. 25–26 August 2020.
51. Saasen, A.; Løklingholm, G. The effect of drilling fluid rheological properties on hole cleaning. In Proceedings of the IADC/SPE Drilling Conference, Dallas, TX, USA, 26–28 February 2002.
52. Saasen, A.; Dahl, B.; Jødestøl, K. Particle Size Distribution of Top-Hole Drill Cuttings from Norwegian Sea Area Offshore Wells. *Part. Sci. Technol.* **2013**, *31*, 85–91. [CrossRef]
53. Dehvedar, M.; Moarefvand, P.; Kiyani, A.R.; Mansouri, A.R. Using an experimental drilling simulator to study operational parameters in drilled-cutting transport efficiency. *J. Min. Environ.* **2019**, *10*, 417–428.
54. Martins, A.; Sa, C.; Lourenco, A.; Campos, W. Optimizing cuttings cisrculation in horizontal well drilling. In Proceedings of the International Petroleum Conference and Exhibition, Villahermosa, Mexico, 5–7 March 1996.
55. Zhu, X.; Shen, K.; Li, B.; Lv, Y. Cuttings Transport Using Pulsed Drilling Fluid in the Horizontal Section of the Slim-Hole: An Experimental and Numerical Simulation Study. *Energies* **2019**, *12*, 3939. [CrossRef]
56. Hirpa, M.M.; Arnipally, S.K.; Bizhani, M.; Kuru, E.; Gelves, G.; Al-Rafia, I. Effect of Particle Size and Surface Properties on the Sandbed Erosion with Water Flow in a Horizontal Pipe. *SPE J.* **2020**, *25*, 1096–1112. [CrossRef]
57. Ling, C.-H. Criteria for Incipient Motion of Spherical Sediment Particles. *J. Hydraul. Eng.* **1995**, *121*, 472–478. [CrossRef]
58. Dey, S.; Sarker, H.K.D.; Debnath, K. Sediment Threshold under Stream Flow on Horizontal and Sloping Beds. *J. Eng. Mech.* **1999**, *125*, 545–553. [CrossRef]
59. Kamp, A.; Rivero, M. Layer modeling for cuttings transport in highly inclined wellbores. In Proceedings of the Latin American and Caribbean Petroleum Engineering Conference, Caracas, Venezuela, 21–23 April 1999.
60. Baldino, S.; Osgouei, R.; Ozbayoglu, E.; Miska, S.; Takach, N. Cutting Settling and Slip Velocity Evaluation in Synthetic Drilling Fluids. In Proceedings of the Offshore Mediterranean Conference and Exhibition, Ravenna, Italy, 25–27 March 2015.
61. Concha, F.; Almendra, E. Settling velocities of particulate systems, 1. Settling velocities of individual spherical particles. *Int. J. Miner. Process.* **1979**, *5*, 349–367. [CrossRef]

62. Zhang, F.; Miska, S.; Yu, M.; Ozbayoglu, E.; Takach, N.; Osgouei, R.E. Is Well Clean Enough? A Fast Approach to Estimate Hole Cleaning for Directional Drilling. In *SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition*; Society of Petroleum Engineers (SPE): Houston, TX, USA, 2015.

63. Gavignet, A.A.; Sobey, I.J. Model Aids Cuttings Transport Prediction. *J. Pet. Technol.* **1989**, *41*, 916–921. [CrossRef]

64. Nguyen, D.; Rahman, S.S. A Three-Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells. *SPE Drill. Complet.* **1998**, *13*, 182–189. [CrossRef]

65. Kelessidis, V.; Badenlis, G. Flow patterns and minimum suspension velocity for efficient cuttings transport in hoizontal and deviated wells in coild-tubing drilling. In Proceedings of the SPE/IcoTA, Houston, TX, USA, 23–24 March 2004.

66. Wilson, K.; Tse, J. Deposition limit for coarse particles transport in inclined pipes. In Proceedings of the International Conference on Hydraulic Transport of Solids in Pipes, Cranfield, UK; 1987.

67. Phillips, M. A force balance model for particle entrainment into a fluid stream. *J. Phys. D Appl. Phys.* **1980**, *13*, 221–233. [CrossRef]

68. Corredor, F.E.R.; Bizhani, M.; Kuru, E. Experimental investigation of cuttings bed erosion in horizontal wells using water and drag reducing fluids. *J. Pet. Sci. Eng.* **2016**, *147*, 129–142. [CrossRef]

69. Ramadan, A.; Skalle, P.; Johansen, S. A mechanistic model to determine the critical low velocity required to initiate the movement of spherical bed particles in inclined channels. *Chem. Eng. Sci.* **2003**, *58*, 2153–2163. [CrossRef]

70. Clark, R.; Bickham, K. A mechanistic model for cuttings transport. In Proceedings of the SPE Technical Conference and Exhibition, New Orleans, LA, USA, 25–28 September 1994.

71. Zou, L.; Patel, M.; Han, G. A new computer package for simulating cuttings transport and predicting hole cleaning in deviated and horizontal wells. In Proceedings of the SPE O&G International Conference and Exhibition, Beijin, China, 26–28 June 2000.

72. Fall, A.; Ovarlez, G.; Hautemayou, D.; Mézière, C.; Roux, J.-N.; Chevoir, F. Dry granular flows: Rheological measurements of the MI-rheology. *J. Rheol.* **2015**, *59*, 1065–1080. [CrossRef]

73. Louati, H.; Oulahna, D.; De Ryck, A. Apparent friction and cohesion of a partially wet granular material in steady-state shear. *Powder Technol.* **2015**, *278*, 65–71. [CrossRef]

74. Badetti, M.; Fall, A.; Hautemayou, D.; Chevoir, F.; Aimedieu, P.; Rodts, S.; Roux, J.-N. Rheology and microstructure of unsaturated wet granular materials: Experiments and simulations. *J. Rheol.* **2018**, *62*, 1175–1186. [CrossRef]

75. Midi, G. On dense granular flows. *Eur. Phys. J. E* **2004**, *14*, 341–365. [CrossRef]