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# Experimental Investigation of the Effects of Blocky Cuttings Transport on Drag and Drive Torque in Horizontal Wells

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**Abstract**

The deposition of large-sized cuttings (or blocky cuttings) is a critical risk factor for stuck pipe incidents during the drilling of deep and extended-reach wells. This risk is particularly pronounced in well sections with long borehole trajectories and low drilling fluid return velocities, where it poses a substantial threat to wellbore cleanliness and the safe operation of the drill string. This study utilizes a self-developed visual experimental platform to simulate the deposition evolution of large-sized cuttings (20–40 mm in diameter) in the annulus under various wellbore inclinations and drilling fluid parameters. The stable height, lateral distribution characteristics, and response patterns of the resulting cuttings bed under different conditions were quantitatively characterized. Building upon this, a theoretical contact friction model between the drill string and the cuttings bed was employed to investigate how the bed height influences hook load during tripping and rotary torque during top drive operation. A mapping relationship was established between cuttings bed structural parameters and the resulting additional loads and torques. Results reveal significant interactive effects among drilling fluid velocity, fluid density, drill pipe rotation speed, and wellbore inclination on both cuttings bed development and associated drill string loads. Strong correlations were identified among these parameters. Based on these findings, a stuck pipe early-warning indicator system is proposed using frictional load thresholds, with clearly defined safety limits for cuttings bed height. Recommendations for optimizing cuttings transport parameters through coordinated control of fluid velocity, density, and rotary speed are also provided, offering theoretical support and engineering guidance for borehole cleaning strategies and stuck pipe risk prediction in large cuttings scenarios.

**Keywords:** large-sized cuttings; solid–liquid two-phase flow; torque and drag; stuck pipe

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## 1. Introduction

With the accelerated transformation of the global energy structure and the steady advancement of China's "carbon peaking and carbon neutrality" strategy, the clean and efficient development of oil and gas resources has become a critical pathway for safeguarding national energy security. Against this backdrop, the exploitation of unconventional natural gas resources—particularly shale gas—has experienced rapid growth. As a type of unconventional gas with challenging reservoir conditions and high development difficulty, shale gas holds irreplaceable strategic value for meeting China's medium- to long-term gas supply needs and reducing reliance on imports. Conventional vertical well development cannot achieve economic production, whereas horizontal drilling—by extending the

wellbore length within productive layers—substantially enhances single-well productivity, making it a key technology for shale gas development. However, as drilling depth increases and reservoir structures become more complex, horizontal well drilling is increasingly confronted with a series of formidable engineering and technical challenges [1].

In deep shale reservoirs (buried depth > 3500 m), wellbore stability issues are particularly severe, primarily due to high in situ stress, pronounced stress anisotropy, formation water sensitivity, and the presence of natural fractures. These geological characteristics intensify stress redistribution around the borehole wall, making it prone to shear failure, collapse, and borehole enlargement. Studies have shown that physicochemical interactions between drilling fluid and formation rock—such as filtrate invasion and shale hydration—can further weaken rock strength, serving as a key mechanism for instability [2,3]. As well depth and horizontal section length increase, wellbore instability worsens and is often accompanied by the rapid generation and accumulation of large-sized cuttings. These blocky cuttings are large in size and settle rapidly, forming thick and unstable cuttings beds at the bottom of the well or around the drill string. They disrupt the annular flow field and reduce cuttings transport efficiency, triggering a cyclical effect of "deposition–transport failure–redeposition." When the drill string enters a blocky cuttings accumulation zone—especially during tripping operations or pump shutdown—burial, sharp increases in hook load, or drill string entrapment may occur, ultimately leading to stuck pipe incidents.

Among the problems arising from borehole instability, stuck pipe incidents are particularly severe, characterized by high frequency, high risk, and high cost. In particular, stuck pipe incidents caused by inadequate hole cleaning—leading to cuttings accumulation and sand bridge formation—are frequently encountered in the field, posing a serious constraint to the safe and efficient drilling of shale gas horizontal wells. Conducting in-depth research on the mechanisms of wellbore stability in shale gas horizontal wells, and systematically analyzing the intrinsic relationship between hole cleaning efficiency and stuck pipe risk, is of significant theoretical and practical value. It supports the optimization of drilling parameters, enhances wellbore stability control capabilities, and promotes high-quality shale gas development.

Field case studies reveal that many stuck pipe incidents are accompanied by distinct downhole characteristics of "blocky cuttings–irregular cuttings bed–high hook load," indicating that the deposition behavior of large-sized cuttings has become a key factor influencing wellbore stability and stuck pipe risk. For example, in the southern Sichuan Basin shale gas block, statistics show that out of 76 wells drilled in the Weiyuan block, 34 experienced stuck pipe incidents due to sand bridge formation, with 21 cases resulting in severe outcomes such as drill string entrapment, borehole abandonment, or premature well termination [4,5]. Stuck pipe incidents not only lead to substantial direct economic losses, but also force engineers to dedicate considerable non-productive time (NPT) to resolving the problems. Thus, wellbore stability issues have thus become a major limiting factor for drilling efficiency and operational timelines, severely impeding the progress of shale gas extraction.

Based on the above incident records and mitigation experiences, the study of cuttings-induced stuck pipe mechanisms in horizontal wells primarily involves two aspects: (1) the transport behavior of cuttings in horizontal wells, and (2) how the cuttings bed exerts resistance on the drill string—i.e., the mechanical response of the drill string under the influence of cuttings.

In studies of cuttings transport behavior in horizontal wells, Tomren et al. [6] conducted cuttings transport experiments in annuli with inclination angles from 0° to 90° using field-generated cuttings, identifying the key factors that influence transport effi-

ciency. Song et al. [7] experimentally investigated the steady-state distribution of cuttings beds during drilling, analyzing the effects of flow velocity, eccentricity, rate of penetration (ROP), drill string-to-borehole diameter ratio, and cuttings size on transport efficiency. Ozbayoglu et al. [8] explored the effect of drill string rotation on cuttings bed distribution in horizontal and inclined wells using water-based drilling fluids, finding that drill string rotation significantly enhances cuttings transport and reduces the critical velocity needed to mobilize stationary cuttings beds. Duan et al. [9] experimentally studied the transport of small-sized cuttings in extended-reach wells, showing that the transport performance varies with the rheological properties of the drilling fluid. Nagawana et al. [10] examined the variation in cuttings concentration across 30–90° inclined well sections under underbalanced drilling conditions. Their results indicated that the flow regime of gas–liquid two-phase flow changes with increasing wellbore inclination, which in turn affects cuttings transport efficiency.

In the study of drill string mechanical response under cuttings influence, the essence of a stuck pipe incident lies in the development of excessive frictional resistance and drive torque acting on the drill string. Johancsik et al. [11] were the first to propose a soft-string torque and drag model, in which the normal contact force responsible for friction was attributed solely to the drill string's weight and axial tension. Recognizing the limitations of the soft-string model—particularly for bottom hole assemblies (BHAs)—Ho [12] developed a stiff-string model that incorporates the effects of drill string stiffness. Sheppard et al. [13] analyzed the influence of wellbore trajectory on drive torque and concluded that catenary-shaped well paths can effectively reduce torque and drag. Wu [14] accounted for the additional normal forces arising from drill string buckling and incorporated them into a refined torque and drag model. Huang et al. [15,16] investigated the buckling behavior of drill strings with tool joints, contributing further to the understanding of axial and lateral contact forces under complex downhole conditions.

However, systematic studies focusing on the deposition behavior of blocky cuttings (with diameters of several centimeters) resulting from wellbore instability under various inclination angles and circulation conditions—along with their impact on cuttings bed evolution and drill string mechanics—remain limited. Existing evaluation methods for cuttings transport are inadequate for capturing the flow field disturbance and localized blockage effects induced by large-sized cuttings in the annulus, nor can they quantitatively predict the relationship between cuttings bed morphology and stuck pipe risk. In response to these challenges, there is an urgent need to establish a coupled experimental–theoretical research framework focused on the deposition behavior of large blocky cuttings. This study utilizes a self-developed visual annular flow experimental platform to move beyond previous paradigms focused primarily on steady-state conditions and small particles. It systematically simulates the deposition behavior of large-sized cuttings under various wellbore inclinations and flow velocities, and quantitatively characterizes their impact on the spatial structure and thickness evolution of the cuttings bed. The focus is placed on revealing the nonlinear disturbance mechanisms of large-sized cuttings on annular flow structure and cleaning efficiency under near-realistic drilling conditions. The study clarifies the complex interactions among particle size, inclination angle, and flow velocity in determining cuttings transport paths and deposition patterns. The experimental results not only deepen the understanding of cuttings transport mechanisms under transient conditions, but also provide foundational data for developing predictive models of large-sized cuttings bed distribution, and they explore the mechanical interaction between cuttings beds and drill strings that results in hook load and torque variations. On this basis, a contact mechanics model between the drill string and cuttings bed is introduced to establish a mapping relationship between drill string burial depth and hook load response,

enabling the development of a stuck pipe risk early-warning indicator system based on drive torque thresholds. Through both experimental observations and model analysis, this study elucidates the evolution mechanisms and engineering risk characteristics of large-sized cuttings deposition, providing theoretical foundations and practical guidance for risk identification, parameter optimization, and borehole cleaning strategy design in deep shale gas drilling.

## 2. Experimental Design, Materials, and Methodology

### *2.1. Experimental Equipment*

This experiment was conducted with a self-developed visual experimental platform apparatus capable of simulating multiphase flow within a wellbore annulus. The system consists of a transparent test section, a liquid circulation unit, and a solid particle injection system, offering dynamic control over multiphase flow conditions. The main wellbore section has an inner diameter of 120 mm, with an internal simulated drill string of 73 mm in outer diameter, and an effective length of 5.5 m. Key structural parameters are shown in Figure 1. To accommodate varying operational scenarios, the base of the platform is equipped with an angular adjustment mechanism that enables continuous variation in the wellbore inclination from 0° to 90°, thereby replicating vertical, inclined, and horizontal well configurations. The fluid circulation unit precisely controls the liquid-phase flow rate, while the particle injection system introduces solid particles of adjustable size and concentration at controlled feed rates. This setup provides a controllable and fully visualized environment for investigating the transient deposition.

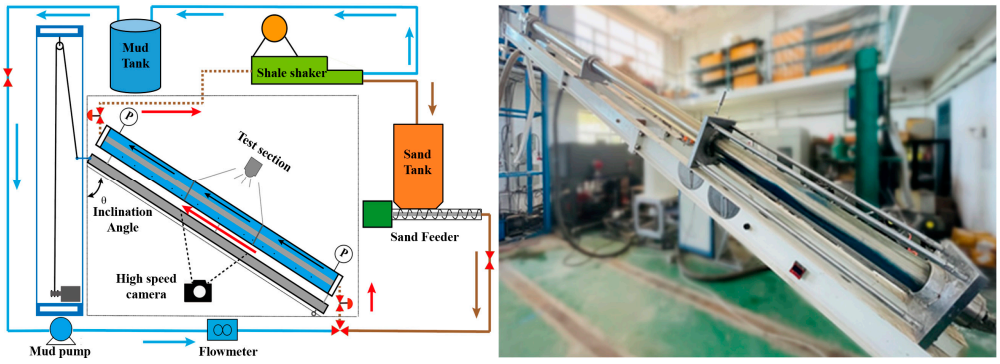



**Figure 1.** Experimental setup: (**a**) schematic diagram of the test facility; (**b**) picture of the cuttings transport test.

### *2.2. Experimental Materials*

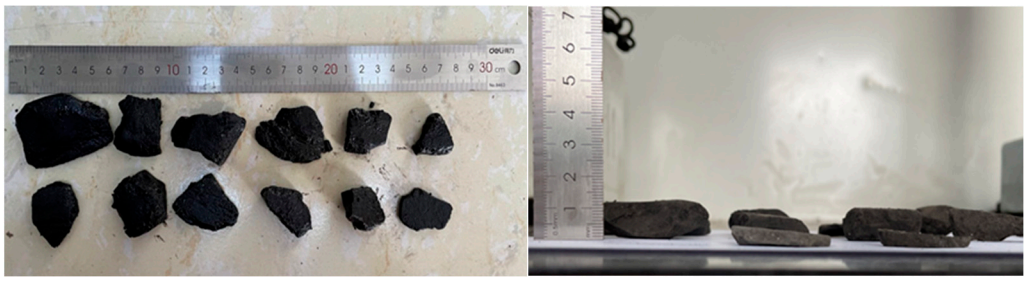
The drilling fluid used in the experiments was sampled directly from a field operation and represents a typical oil-based mud (OBM) system. To characterize the rheological behavior of the fluid under experimental conditions, shear sweep tests were performed using a high-precision rotational rheometer, as shown in Figure 2. To achieve target density values required for the tests, a mixed salt solution of potassium formate was proportionally added to the base OBM, enabling preparation of drilling fluid samples across the desired density range.

To precisely simulate the movement of blocky cuttings within wellbores experiencing instability, samples of blocky cuttings were obtained directly from an active shale gas drilling operation; blocky cutting samples were collected from an actual shale gas drilling site, and the selected material had a particle density of 2.4 g/cm$^3$. After drying, the samples were subjected to standard sieving procedures. Blocky cuttings with particle sizes ranging from 20 to 40 mm were selected as the primary research objects. Their morphological

features are illustrated in Figure 3. To better mimic the geometric characteristics of naturally fractured cuttings in shale formations, the particles were further filtered based on their two-dimensional shape factor—specifically, the Feret diameter ratio [17]—restricted within the range of 0.2 to 0.4. This ensured that the selected particles resembled the irregular, large-sized fragments typically generated by brittle fracturing in shale. This method effectively simplifies the treatment of irregular particle dimensions during experimental analysis and modeling, laying a solid foundation for the subsequent quantitative study of deposition and transport behavior.



**Figure 2.** Oil-based drilling fluid used in the experiment.



(**a**) (**b**)

**Figure 3.** Blocky cuttings from actual shale gas drilling site: (**a**) length of blocky cuttings; and (**b**) height of blocky cuttings.

### *2.3. Experimental Procedure*

To ensure high controllability and repeatability of the experimental fluid system, the purified drilling fluid was then transferred to a designated reservoir tank for subsequent use in driving the annular circulation flow. At the start of each experiment, a prescribed amount of pretreated particle samples was added to the drilling fluid according to the test conditions. A variable-frequency centrifugal pump was then activated, and the flow rate was gradually adjusted to the desired target value. On this basis, a particle injection system was used to uniformly introduce a preset ratio of simulated cuttings and blocky cuttings into the flow field. To capture the transient transport behavior of cuttings within the annulus, a high-speed imaging system was employed to continuously record their motion trajectories, providing dynamic information on key processes such as deposition, suspension, and retention. After the injection process was complete, the liquid–solid mixture passed through a vibrating screen, allowing the drilling fluid to be separated and recovered for reuse in subsequent tests. Once the cuttings bed reached a steady state, predefined scale markers on the transparent pipe wall were used to measure the stable arc length of the bed under various test conditions. Flow rate was then varied via the frequency control system, and the tests were repeated under different wellbore inclinations,

with 90° representing a horizontal well section. For each working condition, once the flow regime stabilized and the cuttings bed morphology ceased to change, the positions of three pre-marked scale points along the wellbore were recorded. These samples were utilized to determine the average arc length ($L$) of the cuttings bed, as illustrated in Figure 4. The resulting arc length data served as the basis for subsequent quantitative analysis of cuttings bed thickness and spatial distribution characteristics [18,19].

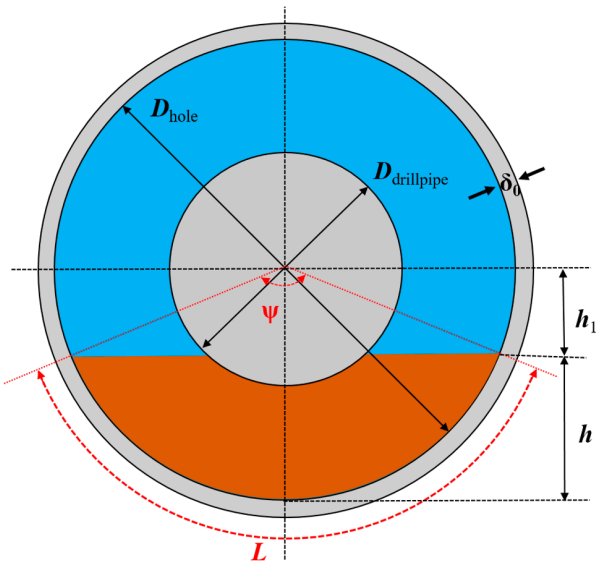



**Figure 4.** The quantitative relationship between arc length and cuttings bed thickness.

In this study, to eliminate the influence of varying wellbore diameters and geometric scales on the evaluation of cuttings bed thickness, a dimensionless cuttings bed height was adopted as the primary descriptive parameter. This parameter is defined as the ratio of the actual cuttings bed thickness to the annular height of the wellbore, and is expressed as follows:

$$\psi = \frac{L}{D_{hole} + 2\delta} \tag{1}$$

$$h_1 = \frac{1}{2} D_{hole} \cos\left(\frac{\psi}{2}\right) \tag{2}$$

$$h = \frac{1}{2} D_{hole} - h_1 \tag{3}$$

$$Dimensionless\ bed\ height = \frac{h}{D_{hole}} \tag{4}$$

Here, $L$ denotes the arc length of the cuttings bed, observed and measured through the transparent outer wall of the test section. $\Psi$ represents the corresponding central angle, indicating the angular extent of the cuttings bed within the circular annular cross-section; $h_1$ is the local vertical thickness of the cuttings bed, used to describe the spatial variation in cuttings bed height along the annulus. $\delta_0$ denotes the wall thickness of the experimental pipe, which serves to correct for observation angle deviations and the boundary between the inner and outer diameters. $D_{hole}$ $D_{\text{hole}}$ and $D_{drillpipe}$ refer to the inner diameter of the wellbore and the outer diameter of the drill pipe, respectively. These are fundamental parameters for calculating annular geometry, including annular height, cross-sectional area, and the dimensionless cuttings bed height.

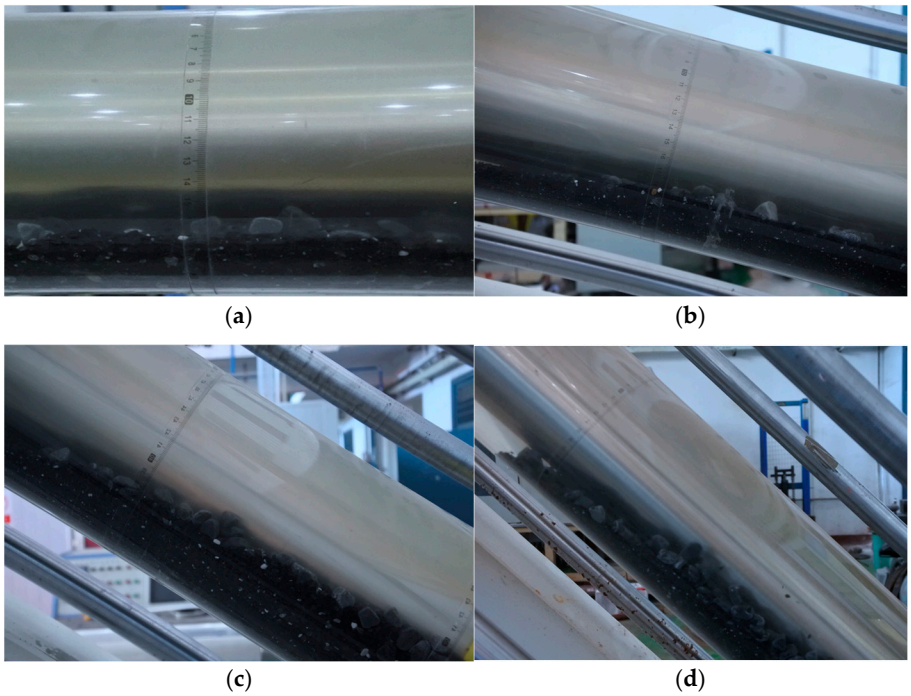
To accurately assess the influence of drilling fluid properties on cuttings transport and hole cleaning efficiency, a comprehensive set of experimental parameters was used. These parameters are critical for simulating realistic wellbore conditions and include flow rate,

well inclination, pipe rotational speed, plastic viscosity (PV), drilling fluid density, and rate of penetration (ROP). Table 1 summarizes these key parameters.

**Table 1.** Detailed table of key experimental parameters.

| Parameter | Unit | Value |
|---|---|---|
| Flow Rate | L/s | 20–40 |
| Well inclination | Deg | 45–90 |
| Pipe rotational speed | Rpm | 50–110 |
| Plastic viscosity (PV) | mPa·s | 40–80 |
| Drilling fluid density | g/cm$^3$ | 1–1.3 |
| Rate of penetration (ROP) | m/h | 2–20 |

As shown in Figure 5, cuttings of different particle sizes exhibited pronounced stratified deposition and transport behaviors within the annulus during the experiments. Large-sized blocky cuttings, dominated by gravitational forces, rapidly settled toward the lower side of the wellbore and progressively accumulated at the bottom of the annulus, forming a dense basal cuttings bed. In contrast, relatively smaller particles were influenced by turbulent shear forces from the fluid and remained temporarily suspended above the basal bed, forming a dilute upper suspension layer. Under low-flow-rate conditions, particle inertia became the dominant factor governing transport behavior. Particles primarily advanced along the annular bottom through rolling, sliding, and intermittent saltation, representing a characteristic "intermittent transport" mode. These upward migration processes led to frequent collisions and disturbances between the large-sized cuttings and the finer particles in the upper suspension zone, triggering localized, periodic deposition–erosion cycles and resulting in the formation of characteristic bedform structures resembling sedimentary ripples. This dynamic restructuring mechanism was manifested in the experiments by reduced flow field stability and periodic fluctuations in flow resistance parameters.



(**a**) (**b**)

(**c**) (**d**)

**Figure 5.** Results of the blocky cuttings transport experiment: (**a**) 90° inclination; (**b**) 75° inclination; (**c**) 60° inclination; and (**d**) 45° inclination.

## 3. Results and Analysis

### *3.1. Transportation Behavior of Blocky Cuttings at Different Flow Rates*

The transport behavior of cuttings and blocky cuttings within the annulus is a critical factor affecting wellbore cleaning efficiency and drilling safety. This is particularly true in long horizontal sections, where their migration characteristics are directly linked to the risk of complex downhole incidents such as stuck pipe and sand bridge formation. Therefore, elucidating the transport response of cuttings with varying particle sizes under multivariable control conditions is of great significance for optimizing cuttings transport systems, improving circulation efficiency, and ensuring wellbore stability.

Among these variables, the annular velocity of the drilling fluid—one of the key parameters governing cuttings transport—exerts a pronounced influence on the motion patterns and migration trajectories of particles with different sizes, as illustrated in Figure 6. This relationship becomes critical when considering the limitations of the drilling fluid to effectively transport larger blocky cuttings, which exhibit markedly different behavior compared to fine drill cuttings. To investigate the underlying mechanisms, a representative set of experimental conditions was selected—including a well inclination of 90°, drilling fluid plastic viscosity of 60 mPa·s, and drill pipe rotation speed of 60 rpm—to systematically analyze how fluid velocity influences the distinct migration behaviors of large blocky cuttings versus fine drill cuttings.

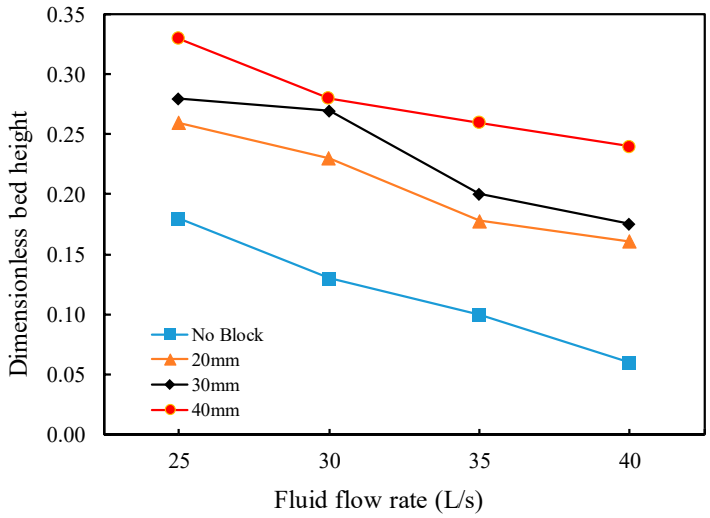



**Figure 6.** Dimensionless bed height affected by flow rate.

The experimental results reveal that as flow velocity increases, both the shear stress and disturbance frequency acting on the particles are significantly intensified. Consequently, particles of different sizes exhibit distinctly divergent behaviors in terms of motion mode, residence location, and deposition stability, especially in the process of transporting cuttings containing 40 mm pieces; when the displacement reaches 40 L/s, the dimensionless cuttings bed height in the annulus can be reduced to $0.26 \pm 0.03$. This effect underscores the critical role of fluid velocity in dictating the efficiency of cuttings removal, particularly when managing large cuttings that are more prone to aggregation and bed formation. These findings provide a foundation for mapping the relationships among particle size, flow velocity, and transport efficiency, offering valuable data and theoretical support for optimizing field-scale cuttings transport parameters and engineering applications.

The impact of flow velocity is directly tied to the particle size, and it reveals a fundamental challenge in transporting large blocky cuttings. At higher velocities, smaller particles are more effectively mobilized, as their lower mass allows them to respond more

quickly to fluid disturbances. However, for larger particles, the increase in shear stress does not necessarily improve transport efficiency; experiments show that it exacerbates settling due to greater drag. The critical issue is that large particles have a higher critical shear stress threshold, which limits their ability to be suspended in the fluid. Thus, while higher velocities help transport smaller cuttings, increased velocity can actually hinder the transport of large blocky cuttings, highlighting the need for a fluid velocity optimization strategy that balances the transport of both fine and coarse cuttings. The practical implication of this is that drilling operations in formations with large blocky cuttings should carefully consider flow velocity settings. Excessive flow velocities, although effective for finer cuttings, may result in inefficient transport of larger particles and lead to cuttings bed formation at the bottom of the wellbore, which in turn increases the risk of stuck pipe incidents and reduced hole cleaning efficiency. Therefore, it is essential to fine-tune the flow velocity to ensure effective transport of both small and large particles, particularly in deep or complex wellbore geometries.

### *3.2. Transportation Behavior of Blocky Cuttings at Different Well Inclinations*

Well inclination serves as a key controlling factor influencing both hole cleaning efficiency and the morphology of cuttings deposition; its variation directly governs the transport paths and accumulation trends of cuttings within the annulus. At high inclination angles, the interplay between gravitational force and fluid drag becomes highly nonlinear rather than linearly additive, leading to significant changes in particle settling velocity and residence locations. Figure 7 illustrates the transport behavior of blocky cuttings (20–40 mm in diameter) and the corresponding development of the cuttings bed under various wellbore inclinations ranging from 30° to 90°. Experimental results indicate that as the well inclination transitions from vertical to horizontal, the thickness of the cuttings bed increases significantly, reflecting a continuous decline in cuttings transport capacity. Notably, at an inclination of 60°, the system exhibited the most pronounced decline in transport performance, indicating a higher propensity for cuttings to settle and form a continuous bed structure at this angle; the maximum height of the dimensionless cuttings bed can reach $0.38 \pm 0.03$. This phenomenon suggests that within the critical inclination zone (approximately 45°to 75°), hole cleaning efficiency becomes highly sensitive to wellbore geometry, and the risk of cuttings accumulation increases markedly.

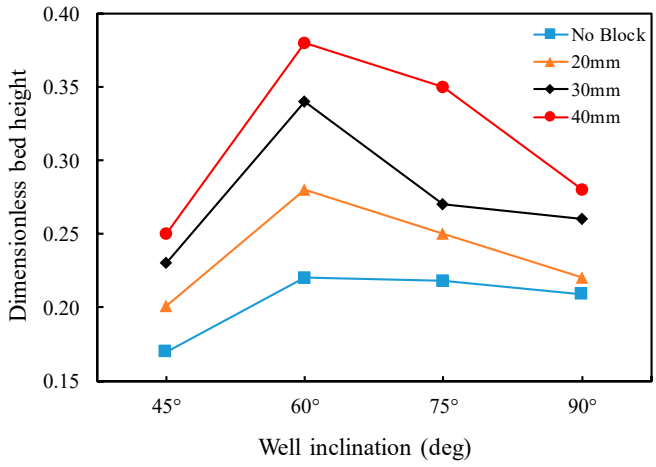



**Figure 7.** Dimensionless bed height affected by well inclination.

The impact of well inclination is particularly critical in high-angle wells where the efficiency of hole cleaning is heavily influenced by the balance between fluid drag and gravity. At inclination angles between 45° and 75°, the fluid's ability to carry particles be-

comes increasingly limited because the drag force is not enough to overcome the increased weight of cuttings. This leads to the accumulation of cuttings at the bottom of the wellbore, resulting in the formation of a cuttings bed. Moreover, as inclination increases, the fluid turbulence and circulation patterns become less effective at mobilizing larger particles. This analysis suggests that for wells in this inclination range, optimizing drilling fluid properties and adjusting flow rates and viscosities could significantly improve hole cleaning and reduce the risk of cuttings bed formation.

### *3.3. Transportation Behavior of Blocky Cuttings at Different Pipe Rotation Speeds*

As shown in Figure 8, the experimental results indicate that the height of the cuttings bed responds significantly to changes in drill pipe rotation speed, and this trend is strongly modulated by particle size.

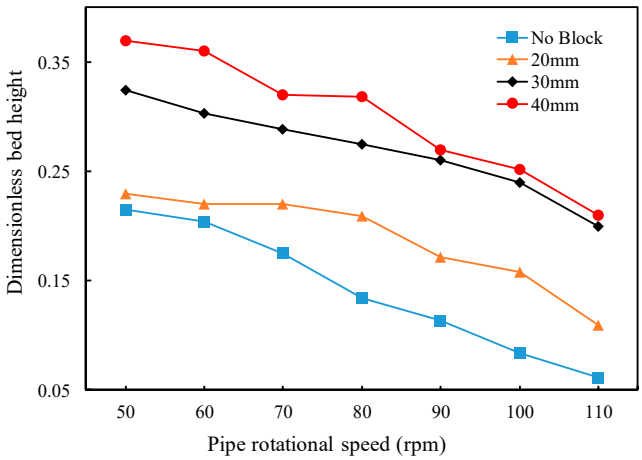



**Figure 8.** Dimensionless bed height affected by pipe rotation speed.

Under identical rotation speeds, increasing the size of the block cuttings from 20 mm to 30 mm increased the cuttings bed thickness by 25–39%, further confirming the dominant role of large-sized cuttings in bed accumulation dynamics. This phenomenon is primarily attributed to the significantly higher critical shear stress required to mobilize larger particles. As particle size increases, the fluid drag acting on them within the drilling fluid also rises, resulting in a pronounced reduction in their slip velocity relative to the surrounding flow. The reduced relative motion leads to decreased momentum transfer per unit time, thereby diminishing the ability of the fluid to mobilize the cuttings. This decline in momentum transfer efficiency increases the energy required for large particles to break free from the settled region, thereby slowing their transport and promoting their retention along the lower side of the wellbore, ultimately forming a thicker and more stable cuttings bed. Consequently, larger particles exhibit a stronger tendency to settle and resist transport under rotational and flow-induced perturbations, highlighting the suppressive effect of particle size on hole cleaning efficiency.

Experimental observations show that when the rotation speed increases to 90 rpm, the rotation-induced secondary flow structures within the annulus are significantly intensified, markedly enhancing the detachment and upward transport of cuttings. This rotational disturbance not only amplifies cross-sectional circulation within the fluid but also generates favorable flow patterns near the drill pipe that promote particle agitation, effectively improving the suspension and migration of blocky cuttings. Specifically, for blocky cuttings in the 30–40 mm size range, increasing drill pipe rotation speed from 60 rpm to 90 rpm improves the transport efficiency from approximately 26% to around 42%, indicating a substantial enhancement in cuttings-carrying performance. The underlying mechanism

lies in the intensified turbulence at higher rotation speeds, which generates shear disturbances with greater frequency and amplitude, helping to overcome the adhesion and static resistance effects associated with large-sized cuttings in the settled state.

Increasing the drill pipe rotational speed induces a significant improvement in hole cleaning efficiency, especially for larger cuttings. The rotational speed increases shear stress and secondary flow turbulence, which are essential for overcoming the tendency of large particles to settle. This is particularly critical in high-angle wells or extended-reach drilling, where secondary flows may be needed to maintain cuttings suspension. However, this approach has limits, and excessive rotation speeds may lead to additional friction and torque issues, complicating the overall drilling operation. Therefore, finding an optimal rotation speed that maximizes the transport efficiency of larger cuttings without overloading the drilling system is crucial for improving the efficiency and safety of drilling operations.

### *3.4. Transportation Behavior of Blocky Cuttings at Different Plastic Viscosities*

The rheological characteristics of drilling fluids, especially plastic viscosity, exert a significant influence on the dynamic behavior of cuttings during transport. Viscosity governs not only the suspension stability of solid particles within the annulus but also the ability of the fluid to generate sufficient shear stress and lift forces to counteract particle settling. As such, it serves as a pivotal factor in determining the overall efficiency of hole cleaning operations. Figure 9 illustrates the variation in cuttings bed height under different plastic viscosity conditions.

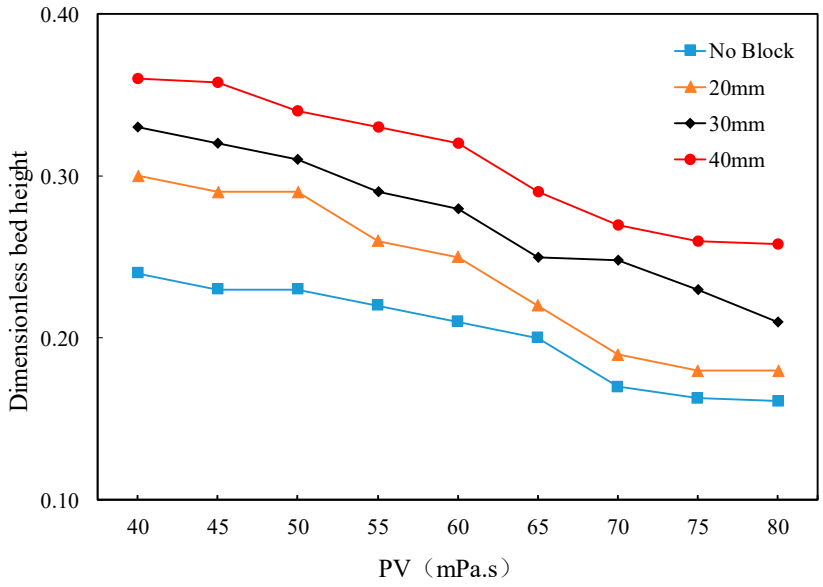



**Figure 9.** Dimensionless bed height affected by plastic viscosity.

Experimental results show that as plastic viscosity increases from a low baseline, the suspension capacity of the drilling fluid improves, leading to reduced particle settling velocity and a marked decrease in the thickness of the cuttings bed at the bottom of the well, thus indicating enhanced hole cleaning effectiveness. However, once the viscosity exceeds approximately 75 mPa·s, the improvement trend plateaus, and further increases in viscosity yield diminishing returns in cleaning performance—an effect herein referred to as the "plateau phenomenon." This phenomenon can primarily be attributed to two underlying hydrodynamic mechanisms: First, increasing viscosity fundamentally alters the flow regime. Under low-viscosity conditions, the system operates in a strong turbulent regime, where random vortices and transient fluctuations greatly enhance the fluid's ability to suspend solid particles—particularly medium to large-sized cuttings. As viscosity

increases beyond a certain threshold, the flow becomes more stratified and transitions into a laminar regime with well-structured velocity layers. In such conditions, vertical momentum diffusion is restricted, weakening the fluid's ability to agitate particles—especially larger blocky cuttings—which become increasingly difficult to mobilize or maintain in suspension. Second, excessive viscosity induces significant pressure losses along the circulation pathway. The elevated viscosity increases frictional resistance, leading to a pronounced rise in pressure drop per unit wellbore length. Such excessive pressure drop not only raises surface pump pressure requirements but may also trigger a range of wellbore stability issues. For instance, an excessively high equivalent circulating density (ECD) may exceed the formation fracture pressure, increasing the risk of lost circulation. Conversely, if annular pressure falls below pore pressure, it may result in well kicks or formation fluid influx—both posing serious operational hazards.

Therefore, higher viscosity is not inherently better; it must be carefully optimized to balance cuttings transport efficiency, flow regime control, and downhole pressure window constraints, thereby achieving coordinated improvement in drilling efficiency and wellbore stability.

The plateau effect observed with plastic viscosity increases highlights that, while higher viscosities can indeed enhance suspension of smaller particles and improve hole cleaning, they are less effective at transporting larger blocky cuttings past a certain threshold. The critical takeaway is that excessively high viscosities do not necessarily improve cuttings transport and may actually reduce the fluid's ability to keep larger cuttings suspended. Based on the preceding hydrodynamic analysis, it is recommended that the plastic viscosity (PV) of the drilling fluid be maintained within an optimal range of 65–75 mPa·s. This range strikes a balance between ensuring effective hole cleaning and mitigating wellbore stability risks. Within this range, the fluid demonstrates a favorable balance between cuttings suspension capacity and flow stability under field conditions, and it is particularly critical for effectively managing blocky cuttings with particle sizes exceeding 30 mm. By carefully controlling viscosity, we can achieve more efficient hole cleaning without compromising wellbore integrity or operational efficiency.

### *3.5. Transportation Behavior of Blocky Cuttings at Different Drilling Fluid Densities*

Drilling fluid density is another key hydraulic parameter governing cuttings suspension and controlling the development of cuttings beds, exerting a significant influence on hole-cleaning efficiency. As illustrated in Figure 10, an increase in drilling fluid density significantly improves the suspension capacity of the fluid system. This enhancement is clearly reflected by the consistent reduction in the thickness of the cuttings bed across the tested density range. Higher fluid density generates greater buoyant force, effectively offsetting the gravitational settling tendency of large-sized cuttings within the annulus. This not only promotes more uniform cuttings distribution but also delays the onset of bed formation, thereby contributing to improved hole cleaning performance in horizontal well sections.

As the fluid density increases from 1000 kg/m$^3$ to 1300 kg/m$^3$, a pronounced reduction in the dimensionless cuttings bed height is observed. Specifically, for cuttings with particle sizes of 20 mm and 40 mm, the bed height decreases by 41.3% and 59.2%, respectively, indicating that high-density drilling fluids significantly suppress particle deposition at the wellbore bottom. This phenomenon is primarily attributed to enhanced buoyant forces. As fluid density increases, the net gravitational force acting on the cuttings is reduced, resulting in a lower effective settling velocity, prolonged suspension time, and increased transport probability. Furthermore, experimental results show that when fluid density exceeds 1.20 g/cm$^3$, the differences in settling behavior among particles of varying sizes

diminish significantly, with the bed heights of 20 mm and 40 mm cuttings converging. This suggests that in high-density fluids, buoyancy and viscous drag become dominant forces in particle settling, thereby masking the mobility differences typically associated with particle size. In such well sections, if cuttings are not promptly transported, they tend to accumulate at the well bottom or in low-velocity zones of the annulus, potentially causing elevated hook loads, reduced rate of penetration, or even stuck pipe incidents. High-density drilling fluids, by increasing both buoyant lift and hydrodynamic drag, help maintain large-sized cuttings in a suspended or slowly drifting state, thereby suppressing early deposition and enhancing overall hole-cleaning efficiency while reducing the risk of annular blockage.

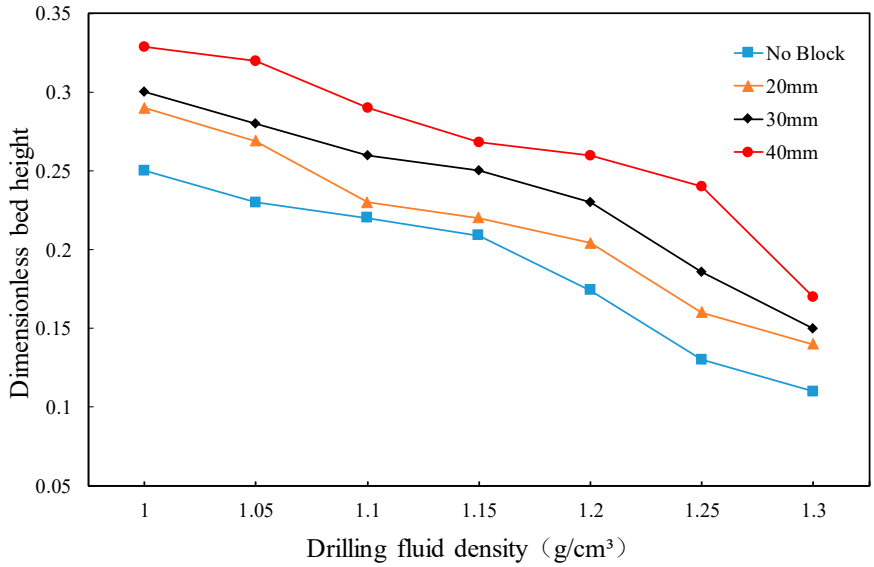



**Figure 10.** Dimensionless bed height affected by drilling fluid density.

However, although increasing drilling fluid density positively enhances cuttings suspension and suppresses particle deposition, the associated engineering challenges must not be overlooked and require careful control and trade-offs in practical applications.

Firstly, as fluid density increases, the hydrostatic pressure of the fluid column rises correspondingly, resulting in elevated annular pressure within the wellbore. If this pressure exceeds the formation's fracture gradient—especially in fragile formations with low fracture pressures—it can induce lost circulation, trigger formation fracturing, compromise wellbore structural integrity, significantly increase non-productive time (NPT), and elevate operational risks. Secondly, increased density is often accompanied by a rise in drilling fluid viscosity, which in turn intensifies frictional pressure losses along the flow path. To maintain the target flow rate, the pumping system must deliver substantially higher power, increasing surface equipment load and energy consumption, thereby reducing the overall efficiency and operational performance of the drilling system. Moreover, high-viscosity, high-density fluids can lead to an "overcompensation" effect in hole cleaning, characterized by diminished shear-induced disturbances and stabilized near-bit flow fields, which paradoxically inhibit particle agitation and transport.

### *3.6. Transportation Behavior of Blocky Cuttings at Different Rate of Penetrations*

The rate of penetration (ROP) is a fundamental operational parameter that directly governs the generation rate of cuttings at the bit. A higher ROP results in a greater volume of cuttings being produced over a given time interval, thereby placing increased demands on the carrying capacity of the drilling fluid. Consequently, ROP exerts a substantial influence on the cuttings transport dynamics within the annulus and serves as a key factor

affecting the overall effectiveness of hole cleaning. Failure to appropriately match ROP with fluid transport capabilities may lead to excessive cuttings accumulation, elevating the risk of bottomhole packing or stuck pipe incidents. Typically, the mechanical drilling rate is defined as the linear velocity of the drill bit advancing axially along the wellbore, measured in meters per hour (m/h). As shown in Figure 11, when the ROP remains below 5 m/h, the volume of cuttings generated per unit time generally remains within the transport capacity of the drilling fluid. Under these conditions, the balance between cuttings production and removal is effectively maintained, leading to the formation of a relatively stable cuttings bed in the annulus without substantial accumulation. This equilibrium minimizes the likelihood of hole cleaning inefficiencies or the development of cuttings-induced flow obstructions.

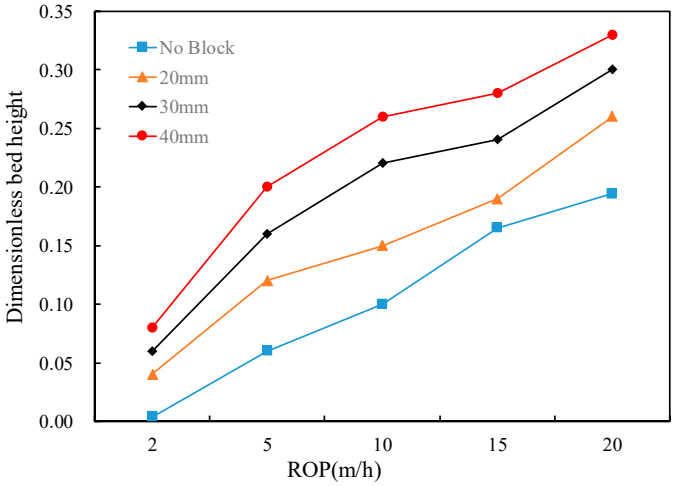



**Figure 11.** Dimensionless bed height affected by rate of penetration.

However, as ROP increases, the volume of cuttings rises rapidly, particularly when the particle size distribution is dominated by large-sized cuttings ranging from 30 to 40 mm. Due to the substantially higher settling velocity of large particles compared to smaller ones, pronounced particle size segregation occurs. Under constant flow conditions, the ability of the drilling fluid to transport solids becomes progressively inadequate as the ROP increases, resulting in a rapid and noticeable growth in cuttings bed thickness within the annular space. Experimental observations reveal that once the ROP surpasses 15 m/h, the rate of cuttings generation significantly exceeds the fluid's transport capacity. This mismatch causes pronounced accumulation of solids near the wellbore bottom, indicating a deterioration in hole cleaning efficiency. In such scenarios, the inability of the drilling fluid to entrain and remove all generated cuttings leads to the formation of a persistent cuttings bed, which may elevate the risk of drilling-related complications such as increased friction, torque, or even stuck pipe incidents. This results in persistent deposition of cuttings at the well bottom region. The substantial accumulation of cuttings severely obstructs the fluid circulation pathways and significantly elevates contact hook load between the drill string and wellbore, increasing the likelihood of differential sticking and severe stuck pipe incidents. Drill string embedment within thick cuttings beds is particularly prevalent in high-angle and extended horizontal well sections, substantially complicating wellbore cleaning and escalating non-productive time (NPT).

Moreover, an increase in ROP is typically accompanied by a rise in the ECD. If not properly controlled, this can cause the wellbore pressure to exceed the formation fracture pressure or the maximum pressure tolerance of downhole equipment, thereby triggering wellbore instability issues such as lost circulation, well kicks, or interlayer cross-flows.

Additionally, geological information—including formation pore pressure, rock mechanical properties, and wellbore inclination—should be comprehensively considered to develop tailored drilling parameter adaptation schemes. Achieving an appropriate balance among higher drilling rates, effective hole cleaning, and wellbore stability is essential for maintaining operational efficiency and safety. By optimizing the interaction between penetration rate and cuttings transport performance, it is possible to enhance drilling efficiency while reducing the likelihood of operational hazards. Specifically, ensuring that the drilling fluid system can adequately manage the increased cuttings load helps to prevent excessive cuttings accumulation, thereby minimizing the risk of stuck pipe events and promoting safe and cost-effective well construction.

## 4. Construction of Torque and Drag Model and Introduction of Additional Effects of Cuttings Bed

In this study, the Torque and Drag Model plays a crucial role in linking the experimental findings on cuttings transport to the mechanical performance of the drilling system. The earlier sections of this work focus on the complex interplay of factors such as flow velocity, viscosity, well inclination, and particle size on cuttings behavior within the annulus. These factors directly affect the distribution, migration, and deposition of blocky cuttings, which in turn influence hole cleaning efficiency. As cuttings accumulate and form beds within the wellbore, they exert frictional resistance on the drill string, leading to increased torque and drag. This resistance, if left unchecked, can elevate the likelihood of operational complications such as stuck pipe incidents. The Torque and Drag Model quantitatively integrates the effects of these cuttings beds on the forces acting on the drill string, particularly the frictional forces, and translates them into practical parameters such as hook load, torque, and mechanical stress. The model's application is, therefore, an extension of the earlier experimental observations, which identified the challenges posed by cuttings accumulation. By explicitly modeling the impact of these accumulations on the drilling system's mechanical performance, the Torque and Drag Model provides a more comprehensive understanding of how cuttings transport efficiency and hole cleaning influence overall wellbore stability. Furthermore, it serves as a predictive tool for optimizing drilling parameters, allowing engineers to mitigate risks associated with excessive torque and drag, and ultimately improving the safety, efficiency, and cost-effectiveness of drilling operations.

### *4.1. Conventional Torque and Drag Model*

Existing models for the calculation of hook load and drive torque generally fall into two categories: the soft-string model and the stiff-string model. In this study, the soft-string model is employed for analysis. First proposed by Johancsik et al. [11] in 1984, the soft-string model is a simplified mechanical framework designed to characterize drill string motion within the wellbore. It is primarily used to assess the dynamic loads acting on the drill string and its mechanical stability. By neglecting the influence of drill string stiffness, the model offers computational simplicity and reliability. Under conditions of low wellbore curvature and smooth borehole surfaces, the soft-string model provides sufficiently accurate estimates of friction and torque, particularly for drill string sections composed of low-stiffness conventional drill pipes. Consequently, it has been widely adopted in drilling engineering applications.

The soft-string model adopted in this study is based on the following assumptions: (1) The drill string is treated as a flexible rod with negligible stiffness; its bending stiffness is extremely small, so the influence of the elastic stiffness of the drill string itself on the stress and deformation is ignored; (2) the borehole wall is considered rigid, and drill string

movement is constrained to strictly follow the wellbore trajectory; complex practical factors such as wellbore ellipticity, wall elastic deformation, and lateral drill string vibration are not considered. Furthermore, the model focuses on the impact of the cuttings bed on the steady-state torque and friction of the drill string during drilling, and does not consider the transient fluctuations of dynamic drill string vibration and shear force; (3) shear forces on the drill string cross-section are neglected; (4) dynamic effects are excluded, with only static equilibrium considered; and (5) the wellbore trajectory is assumed to lie in a two-dimensional plane, and azimuthal variations are not accounted for in the friction and torque calculations.

Following the segmented mechanical recursion model established by Gao et al. [20], and assuming an ideal clean-hole condition without cuttings accumulation, the sources of drag are limited to two primary contributors: the component of the unit string weight acting along the deviated well path and the contact friction force between the drill string and the borehole wall. Drive torque is similarly attributed to frictional resistance generated by rotational motion of the drill string.

For extended-reach horizontal wellbores, the baseline frictional drag (i.e., the frictional force in the absence of cuttings accumulation) can be calculated using the following equation:

$$F_{i+1} = F_i + q \cdot L_u \cdot (\cos\alpha \pm \mu \sin\alpha) \tag{5}$$

Here, $F_{i+1}$ and $F_i$ represent the axial loads at two adjacent nodes, N; $q$ is the buoyancy-corrected unit weight of the drill string, N/m; $L_u$ denotes the segment length, m; $\mu$ is the friction coefficient, and $\alpha$ is the inclination angle of the segment, °; and the "±" sign corresponds to tripping in (−) and tripping out (+) operations, respectively.

The buoyancy-corrected unit weight $q$ of the drill string is calculated using the following expression:

$$q = \frac{W}{L}\left(1 - \frac{\rho_f}{\rho_s}\right) \tag{6}$$

where $W$ is the total weight of the drill string in air, N; $L$ is the total length of the drill string, m; $\rho_f$ is the density of the drilling fluid, kg/m$^3$; and $\rho_s$ is the density of the drill string material, kg/m$^3$.

Under rotary drilling conditions, relative sliding occurs between the drill string and the borehole wall, generating frictional resistance torque. The baseline drive torque can be calculated as follows:

$$T_{i+1} = T_i + \mu \cdot F_n \cdot \frac{D_p}{2} \tag{7}$$

In this equation, $T_{i+1}$ and $T_i$ are the cumulative torques at two adjacent nodes, N·m; $F_n$ is the normal contact force acting on the segment, N; $D_p$ is the outer diameter of the drill string, m; this model is applicable under the condition of continuous drill string rotation with borehole wall contact.

The normal force $F_n$ can be further expressed as follows:

$$F_n = q \cdot L_u \cdot \sin\alpha \tag{8}$$

The above model serves as the foundational computational framework in this study and is employed to compare variations in drag and torque before and after cuttings bed formation.

### *4.2. Additional Drag and Torque Model for Cuttings Bed*

After the formation of a large-sized cuttings bed, the contact environment between the drill string and the borehole is significantly altered. The accumulated cuttings form a bed

along the drill string trajectory, exhibiting characteristics of a quasi-rigid granular medium, which imposes substantial additional resistance during axial movement or rotation of the drill string. This additional resistance arises from two primary mechanisms: (1) the "bulldozing effect" caused by the drill string pushing through the cuttings bed, which manifests as additional axial drag; and (2) shear friction between the cuttings and the drill string surface during rotation, resulting in torque increments.

In this study, the additional torque and drag models were adopted from Tan [21] to quantify the effects of cuttings accumulation on drilling dynamics, specifically the drag and torque acting on the drill string. The model is highly applicable to the study's focus on blocky cuttings transport and deposition, as it accurately captures the impact of cuttings on wellbore stability in horizontal wells. By incorporating key parameters such as cuttings bed thickness, particle size distribution, and fluid properties, these parameters are crucial for understanding the frictional forces that contribute to wellbore instability and stuck pipe risks, particularly in the presence of large, blocky cuttings; the model provides a robust framework for evaluating the frictional forces that contribute to wellbore instability and stuck pipe risks. Moreover, the inclusion of additional torque and drag terms enhances the predictive capabilities of the study, providing a more detailed understanding of how operational parameters, including drilling fluid rheology, flow rate, and well inclination, affect cuttings transport efficiency. This approach establishes a direct connection between cuttings transport efficiency and the mechanical forces acting on the drill string, offering deeper insights into the wellbore cleaning process.

Under conditions such as tripping out or back reaming, the cuttings bed accumulates against step shoulders or the drill string front, forming a blockage, and the additional axial thrust is expressed in Tan [21] as follows:

$$F_a = F_{fs} \cdot \exp\left(\frac{4kf_w D_b L_c}{D_b^2 - D_p^2}\right) \tag{9}$$

where $F_a$ is the additional axial drag, N; $F_{fs}$ is the direct thrust exerted by the cuttings bed on the step shoulder, N; $k$ is the lateral pressure coefficient of the cuttings; $f_w$ is the friction coefficient between the cuttings and the shoulder surface; $D_b$, $D_p$ are the outer diameters of the step and the drill string, m, respectively; and $L_c$ is the accumulation length of the cuttings bed, m.

Under reaming conditions, the cuttings bed encloses the drill string and generates shear resistance. The torque increment can be modeled as the frictional moment exerted by the cuttings column on the drill string surface [21]:

$$T_t = \frac{F_a f_p D_p^2}{2 f_w D_b}\left[1 - \exp\left(-\frac{4kf_w D_b L_c}{D_b^2 - D_p^2}\right)\right] \tag{10}$$

where $T_t$ is the additional torque, N·m, and $f_p$ is the friction coefficient between the cuttings and the drill string surface.

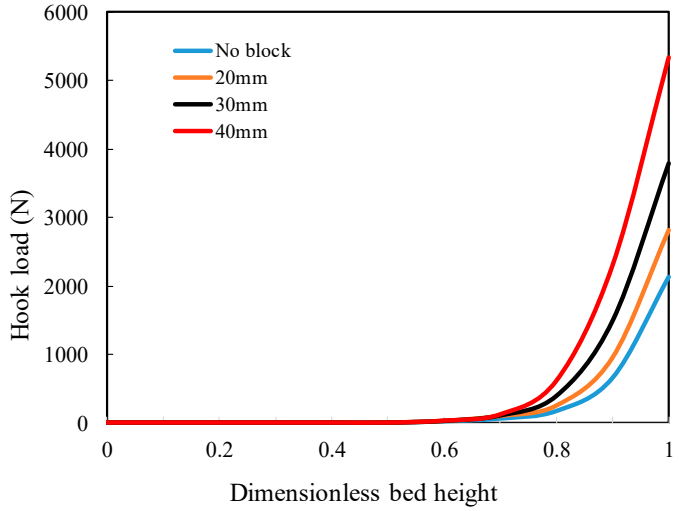
Based on the experimentally obtained distribution and height of the large-sized cuttings bed under various conditions, along with known borehole geometry, drill string diameter, and cuttings bed density, the additional drag and torque can be quantitatively evaluated. Furthermore, by incorporating the additional terms from Equations (5) and (7) into the baseline model, a complete predictive model for drag and torque, $F^*_{i+1}$ and $T^*_{i+1}$, can be constructed.

$$F^*_{i+1} = F_{i+1} + F_a \tag{11}$$

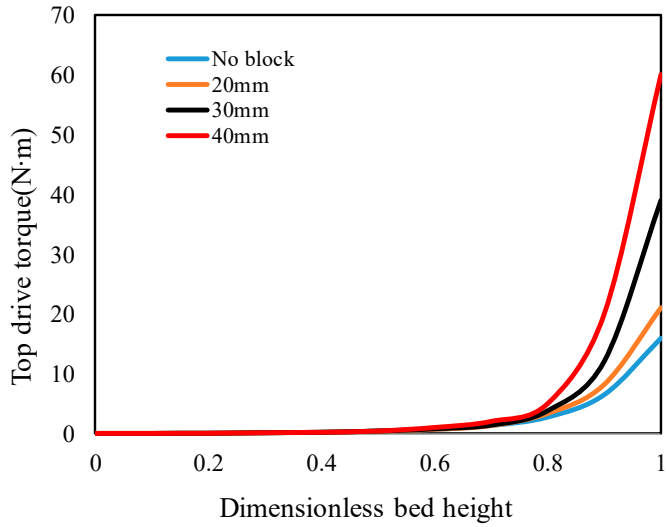
$$T^*_{i+1} = T_{i+1} + T_t \tag{12}$$

*4.3. Sensitivity Analysis of Additional Drag Torque on Cuttings Bed Height*

To further investigate the mechanical influence of large-sized cuttings beds on drill string loading, a sensitivity analysis of additional load responses was conducted using cuttings beds composed of blocky cuttings with different particle sizes. Based on previously obtained experimental data on cuttings bed formation, three representative particle sizes (20 mm, 30 mm, and 40 mm) were selected to construct various bed height scenarios, and their effects on additional hook load and top-end torque under tripping and rotary conditions were systematically analyzed. Figure 12a presents the relationship between additional hook load and dimensionless cuttings bed height ($h/D_{\text{hole}}$) under different blocky cuttings size conditions.




(**a**)




(**b**)

**Figure 12.** Additional hook load and torque of drill pipe at different dimensionless bed heights: (**a**) additional hook load; and (**b**) additional torque.

The analysis shows that when the dimensionless bed height is less than 0.6, the axial obstruction from the cuttings bed is limited, with the additional hook load typically below 1 kN, indicating negligible drag effects per unit length. At this stage, cuttings mainly accumulate at the bottom of the annulus without forming a continuous bed, and their influence on the hook load per unit length is minimal and insufficient to significantly

hinder drill string movement. However, when the dimensionless height exceeds 0.6, the additional hook load exhibits exponential growth. The cuttings bed begins to form an effective pushing interface with the drill string, leading to sustained contact and rapid accumulation of drag force, displaying a typical nonlinear enhancement effect. For example, with 20 mm particles, once the cuttings bed fully blocks the annulus, the additional hook load can reach approximately 2000 kN, significantly increasing the risk of stuck pipe due to insufficient surface pull force. Moreover, larger particle sizes result in higher additional hook loads. When the dimensionless bed height exceeds 0.8, the additional hook load from the 40 mm bed is approximately 35% higher than that from the 30 mm bed. This trend is attributed to the greater tendency of larger particles to form irregular arching structures and interlocking frameworks during accumulation, resulting in deeper inter-particle embedding and higher lateral pressures that intensify pushing resistance.

Additionally, although large particles exhibit lower packing efficiency in the annulus, they form denser contact networks at the same bed height, increasing the number of effective friction points per unit volume and amplifying the bulldozing effect, thereby further raising the additional load. Figure 12b illustrates the variation in additional top drive torque with respect to the dimensionless height of the cuttings bed. Overall, the additional torque increases progressively with bed height, and the trend remains consistent across different particle sizes. The analysis shows that when the dimensionless bed height is below 0.5, torque growth is slow, indicating a primary stage of resistance with limited shear path and small contact area. Once the bed height exceeds 0.5, torque response intensifies, especially after full annulus occupation, where the additional shear resistance approaches or exceeds the rated capacity of the top drive. The maximum additional torques caused by no cuttings and cuttings of 20 mm, 30 mm, and 40 mm sizes were 16.7 kN·m, 21.2 kN·m, 39.6 kN·m, and 60.7 kN·m, respectively. The 40 mm cuttings bed induces significantly higher additional torque than the 30 mm and 20 mm cases. This is due to the greater rolling resistance and tangential interlocking during drill string rotation, along with simultaneous sliding and rotational friction between particles, forming a compound shear resistance structure that greatly increases torque. In contrast, smaller particles are more easily disturbed or redistributed under rotary motion, resulting in a weaker shear resistance effect. The results indicate that larger particles and higher bed layers significantly increase rotary load, potentially causing top drive overload, drill string slippage, stoppage, or even stuck pipe incidents. Even at constant bed height, particle size remains a critical structural factor influencing drill string response, with effects being more pronounced under high bed heights and dense particle interlocking. In field operations, inadequate hole cleaning may cause large-sized blocky cuttings to accumulate near the bottom, and even a thin bed may induce severe drag and torque amplification due to particle size effects, constituting a major risk for stuck pipe events.

### *4.4. Risk Assessment of Drill Sticking Considering the Cuttings Bed*

To investigate the mechanism by which different distribution patterns of cuttings beds influence stuck pipe incidents caused by sand deposition, this section establishes a wellbore structural model to analyze the effects of annular cuttings beds on hook load and surface torque increments under various conditions at a drill bit depth of 4000 m. Given that drilling incidents frequently occur during tripping out and back-reaming operations, this section focuses on analyzing the variations in hook load and surface torque under these two operational states and their correlation with stuck pipe occurrences. Considering the horizontal well depth of 4000 m in this study, simulations utilize the ZJ50J drilling rig and DQ70BSD top drive system, suitable for wells between 3000 m and 6000 m depth. The ZJ50J rig has a maximum rated hook load of 3150 kN, and the DQ70BSD top drive has

a maximum rated torque of 60 kN·m. The simulation parameters—including wellbore and drill string dimensions, cuttings density, drilling fluid density, and cuttings particle size—are consistent with those used in the cuttings migration experiments in Section 3. Friction coefficients between the cuttings bed and wellbore wall and between the cuttings bed and drill string are set to 0.3 and 0.1, respectively, based on Li et al.'s experimental data [22]. The bit torque is 3 kN·m, the traveling block weight is 220 kN, and the sliding friction coefficient is 0.3.

To quantitatively investigate the effect of average cuttings bed height on friction and torque response along the wellbore section, this study focuses on the high-angle and horizontal sections of the well. The interval with a wellbore inclination angle greater than 60° between 1560 m and 4000 m is designated as the main cuttings accumulation zone. It is assumed that within this interval, the average cuttings bed height is uniformly distributed along the section, with the bed thickness treated as a first-order control variable. The simulation conditions select the drill bit position at a depth of 4000 m to analyze the increments in hook load and rotary table torque generated during tripping out as the drill string moves upward from the horizontal section through to the cuttings bed zone. Figure 13 illustrates the response characteristics of hook load variation with well depth during tripping out under different dimensionless cuttings bed heights. The tripping out path covers the interval from the high-angle section at 1560 m depth to the horizontal well bottom at 4000 m depth, simulating the axial additional load variations caused by cuttings bed accumulation.

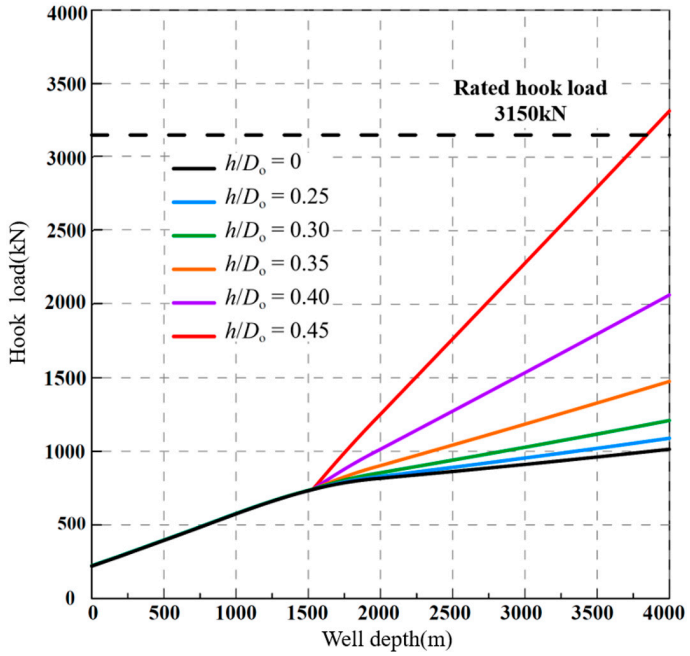



**Figure 13.** Hook load under tripping-out conditions with varying dimensionless cuttings bed heights.

The figure shows that from the well depth of 1560 m, as the well depth increases, the additional value of the cuttings bed to the hook load gradually increases and reaches the maximum at the bottom of the well (4000 m). This trend reflects the typical "length-accumulation" characteristic of the cuttings bed's contribution to the hook load; the longer and thicker the cuttings bed, the greater the pushing friction resistance the drill string must overcome. Under ideal clean wellbore conditions without cuttings accumulation, the maximum hook load during tripping out is 1014.4 kN, significantly lower than the rig's rated hook load of 3150 kN, indicating safe operation. When the dimensionless cuttings bed height is less than 0.25, the additional axial load induced by the cuttings bed is weak, with

hook load increases generally under 10%, allowing the system to maintain stable operation. However, once the dimensionless cuttings bed height exceeds 0.25, the hook load shows an accelerated upward trend, and, at 0.45, simulation results indicate a hook load of 3313.6 kN, exceeding the rig's rated load limit. At this stage, the tripping resistance includes not only the drill string's self-weight and basic friction but also the large-scale particle accumulation and blocking force imposed by the cuttings bed against the ledge, manifesting a pronounced bulldozing effect. If the cuttings bed height continues to increase, the additional friction will rise at a steeper rate, placing the hook load system at severe overload risk. Therefore, from a tripping safety perspective, when the dimensionless cuttings bed height approaches or exceeds 0.45, continuous upward tripping operations should be performed with caution. It is recommended to prioritize wellbore cleanliness evaluation and cuttings bed height monitoring before tripping and, if necessary, use agitation tools or high-rate circulation to clear bottom deposits, thereby reducing tripping resistance and preventing stuck pipe due to insufficient hook load.

Figure 14 illustrates the variation trends of hook load and top drive torque with well depth during back reaming operations under different dimensionless cuttings bed heights. The simulation path also covers the high-angle section with well inclination greater than 60° and the horizontal section (1560 m–4000 m), focusing on the differences in the effects of cuttings bed accumulation on the drill string's mechanical response.

As shown in Figure 14a, the trend of hook load variation largely aligns with that observed during tripping out; the additional load imposed by the cuttings bed accumulates progressively with the length of the drill string traversing the section, increasing gradually from 1560 m and peaking at the well bottom. However, unlike the tripping-out condition, under ideal clean wellbore conditions without cuttings accumulation, the hook load during back reaming is 721.7 kN, significantly lower than the 1014.4 kN observed during tripping out. This difference arises because during back reaming the drill string is simultaneously rotated and pulled axially; the rotational disturbance partially undermines the structural stability of the cuttings bed, reducing its pushing resistance and thereby lowering the axial additional load.

Furthermore, even with increasing the cuttings bed height, the increment in hook load caused by back reaming remains relatively limited. When the dimensionless cuttings bed height reaches 0.45, the hook load rises to 3022.5 kN, which, while close to the rig's rated hook load of 3150 kN, remains within tolerance limits, indicating that cuttings accumulation imposes a burden but has not exceeded system limits.

In contrast, the top drive torque is more significantly affected by the cuttings bed during back reaming, exhibiting pronounced nonlinear amplification characteristics as shown in Figure 14b. Under clean conditions without a cuttings bed, the top drive torque is 29.8 kN·m; when the cuttings bed height increases to 0.40, the torque reaches 58.18 kN·m, approaching the equipment's rated torque of 60 kN·m; further increasing to 0.45, the torque rapidly jumps to 91.6 kN·m, exceeding the safe operational limit by 52%, indicating an explosive increase in cuttings shear resistance at this stage. This phenomenon primarily results from the constant drill string rotation speed during back reaming combined with enhanced integrity of the cuttings bed structure, an expanded shear surface, and intensified friction and compression at the particle–drill string interface, leading to a sharp rise in shear force exerted per unit length of the cuttings bed. Additionally, during tripping, the bit drives the ledge surface backward, forming localized compaction zones that exacerbate the accumulation of rotational friction.

Integrating the hook load and top drive torque metrics reveals that, during back reaming, the cuttings deposition restricts torque much more significantly than axial load. Once the cuttings bed height exceeds the critical threshold (in this case, a dimensionless

height greater than 0.4), the top drive torque is prone to overload risk, acting as the primary triggering factor for stuck pipe incidents caused by sand deposition. Therefore, when conducting back reaming in high-angle well sections or areas with low return flow velocity, priority should be given to monitoring the top drive system status and establishing a dynamic wellbore cleanliness early warning system characterized by abrupt torque rate changes.

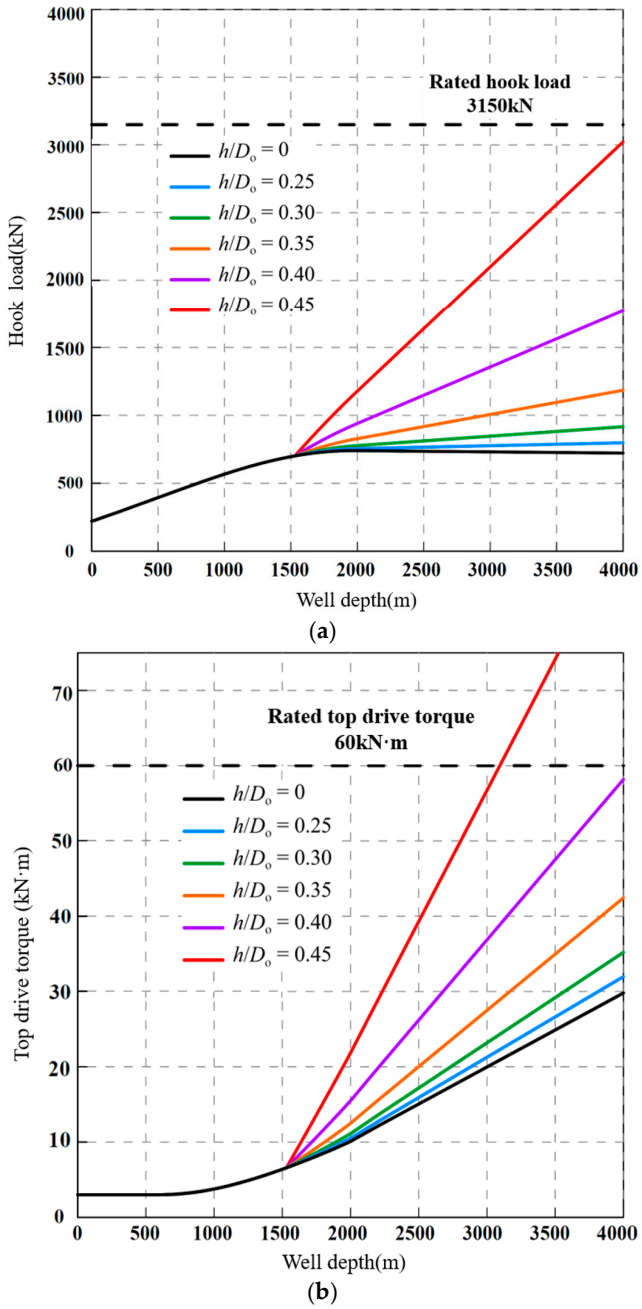



**Figure 14.** Hook load and torque under back-reaming conditions with varying dimensionless cuttings bed heights: (**a**) hook load; and (**b**) top drive torque.

## 5. Conclusions

Based on systematic experimental studies of blocky cuttings transport and simulations of drill string mechanical response, this paper reveals the formation mechanisms of large-sized cuttings beds under various drilling parameters and their influence on drag, drive torque, and stuck pipe risk. The main conclusions are as follows:

(1) Cuttings size significantly regulates transport efficiency and cuttings bed height. As the cuttings size increases from 20 mm to 40 mm, their residence time in the annulus significantly increases, suspension capability decreases, and the average cuttings bed height rises markedly. Under a 90° well inclination, the dimensionless bed height formed by 40 mm cuttings reaches 0.42, significantly higher than the 0.28 for 20 mm cuttings under identical conditions, indicating that larger cuttings substantially intensify bottomhole sedimentation and are more likely to form continuous bed structures.

(2) Drilling fluid flow rate, drill string rotation speed, and fluid density strongly influence the suppression and removal of cuttings beds. Experimental results show that when the drilling fluid velocity is insufficient, the drill string speed is below 60 rpm, and when the fluid density is less than 1.1 g/cm$^3$, the cuttings bed becomes more structurally stable and its thickness increases. In contrast, increasing fluid flow rate (>35 L/s), rotational speed (>90 rpm), and density (~1.25 g/cm$^3$) enhances fluid shear capacity and particle agitation frequency, improving detachment and transport efficiency of large-sized cuttings, enabling control of bed height below 0.25, which is essential for maintaining wellbore cleanliness.

(3) High rates of penetration (ROP) and large blocky cuttings fractions significantly accelerate cuttings bed accumulation. Experimental results demonstrate that when the ROP exceeds 15 m/h, the cuttings bed thickness increases sharply. In this condition, the rate of sedimentation at the wellbore bottom significantly surpasses the cuttings transport capacity of the drilling fluid, leading to unstable cuttings accumulation and severe disruption of the annular flow regime. This imbalance substantially elevates the risk of stuck pipe incidents caused by excessive sand buildup. To mitigate such risks, it is essential to implement a dynamic ROP control strategy in conjunction with real-time optimization of drilling fluid properties, thereby establishing an integrated "generation–transport–removal" mechanism to sustain continuous and effective hole cleaning.

(4) Cuttings bed height exhibits an exponential amplifying effect on frictional resistance and hook load during tripping out. When the dimensionless cuttings bed height is below 0.25, the increase in hook load remains below 10%, and the frictional impact is manageable. However, when the bed height exceeds 0.45, the hook load increases rapidly, with the maximum simulated load reaching 3313.6 kN, surpassing the rig's rated hook load (3150 kN), indicating that once bed thickness exceeds a critical threshold, it drastically raises axial load, triggering a high risk of sand-induced stuck pipe.

(5) Torque response is more sensitive to cuttings bed height and serves as an early indicator of stuck pipe events. Under back reaming conditions, although the hook load does not exceed limits (maximum of 3022.5 kN), when the dimensionless cuttings bed height reaches 0.45, the top drive torque surges to 91.6 kN·m, far exceeding the rated torque limit of 60 kN·m, indicating significant overload risk. Compared to the hook system, the top drive system is more prone to early failure due to cuttings shear resistance, suggesting that torque overload triggered by cuttings beds serves as a critical early-warning sign of stuck pipe risk.

(6) Based on combined transport experiments and load simulations, a critical cuttings bed height threshold for stuck pipe risk is proposed. Based on multivariable analyses of cuttings transport behavior across particle sizes and torque-load response modeling, the dimensionless bed height should be kept below 0.25 for safe-clean zones, 0.25–0.40 for risk transition zones, and above 0.40 for high-risk stuck pipe zones. In field wellbore cleanliness evaluations, real-time monitoring of cuttings bed evolution and

load margin assessment should be combined to implement dynamic control strategies, preventing progression to critical states.

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## References

1. Epelle, E.I.; Gerogiorgis, D.I. A Review of Technological Advances and Open Challenges for Oil and Gas Drilling Systems Engineering. *AIChE J.* **2020**, *66*, e16842. [CrossRef]
2. Gautam, S.; Guria, C. Optimal Synthesis, Characterization, and Performance Evaluation of High-Pressure High-Temperature Polymer-Based Drilling Fluid: The Effect of Viscoelasticity on Cutting Transport, Filtration Loss, and Lubricity. *SPE J.* **2020**, *25*, 1333–1350. [CrossRef]
3. Sun, X.; Tao, L.; Qu, J.; Yao, D.; Hu, Q. Evaluating the Effectiveness of Cleaning Tools for Enhanced Efficiency in Reamed Wellbore Operations. *Geoenergy Sci. Eng.* **2025**, *246*, 213620. [CrossRef]
4. Zhu, N.; Huang, W.; Gao, D. Numerical Analysis of the Stuck Pipe Mechanism Related to the Cutting Bed under Various Drilling Operations. *J. Pet. Sci. Eng.* **2022**, *208*, 109783. [CrossRef]
5. Chen, Y.; Li, W.; Wang, X.; Wang, Y.; Fu, L.; Wu, P.; Wang, Z. Research and Application of Geomechanics Using 3D Model of Deep Shale Gas in Luzhou Block, Sichuan Basin, Southwest China. *Geosciences* **2025**, *15*, 65. [CrossRef]
6. Tomren, P.H.; Lyoho, A.W.; Azar, J.J. Experimental Study of Cuttings Transport in Directional Wells. *SPE Drill. Eng.* **1986**, *1*, 43–56. [CrossRef]
7. Song, X.; Xu, Z.; Wang, M.; Li, G.; Shah, S.N.; Pang, Z. Experimental Study on the Wellbore-Cleaning Efficiency of Microhole-Horizontal-Well Drilling. *SPE J.* **2017**, *22*, 1189–1200. [CrossRef]
8. 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; p. SPE-114965-MS.
9. Duan, M.; Miska, S.; Yu, M.; Takach, N.; Ahmed, R.; Zettner, C. Transport of Small Cuttings in Extended-Reach Drilling. *SPE Drill. Complet.* **2008**, *23*, 258–265. [CrossRef]
10. Naganawa, S.; Oikawa, A.; Masuda, Y.; Tetsuo, Y.; Hoshino, M.; Acuna, P. Cuttings Transport in Directional and Horizontal Wells While Aerated Mud Drilling. In Proceedings of the IADC/SPE Asia Pacific Drilling Technology, Jakarta, Indonesia, 7–9 September 2002; p. SPE-77195-MS.
11. Johancsik, C.A.; Friesen, D.B.; Dawson, R. Torque and Drag in Directional Wells-Prediction and Measurement. *J. Pet. Technol.* **1984**, *36*, 987–992. [CrossRef]
12. Ho, H.-S. An Improved Modeling Program for Computing the Torque and Drag in Directional and Deep Wells. In Proceedings of the SPE Annual Technical Conference and Exhibition, Houston, TX, USA, 2 October 1988; p. SPE-18047-MS.
13. Sheppard, M.C.; Wick, C.; Burgess, T. Designing Well Paths to Reduce Drag and Torque. *SPE Drill. Eng.* **1987**, *2*, 344–350. [CrossRef]
14. Wu, J. Slack-off Load Transmission in Horizontal and Inclined Wells. In Proceedings of the SPE Production Operations Symposium, Oklahoma City, OK, USA, 2–4 April 1995; p. SPE-29496-MS.
15. Huang, W.; Gao, D.; Liu, Y. Buckling Analysis of Tubular Strings with Connectors Constrained in Vertical and Inclined Wellbores. *SPE J.* **2017**, *23*, 301–327. [CrossRef]

16. Huang, W.; Gao, D.; Liu, Y. Inter-Helical and Intra-Helical Buckling Analyses of Tubular Strings with Connectors in Horizontal Wellbores. *J. Pet. Sci. Eng.* **2017**, *152*, 182–192. [CrossRef]
17. Wadell, H. Volume, Shape, and Roundness of Rock Particles. *J. Geol.* **1932**, *40*, 443–451. [CrossRef]
18. Sun, X.; Yao, D.; Qu, J.; Sun, S.; Qin, Z.; Tao, L.; Zhao, Y. A Novel Transient Hole Cleaning Algorithm for Horizontal Wells Based on Drift-Flux Model. *Geoenergy Sci. Eng.* **2024**, *233*, 212517. [CrossRef]
19. Yao, D.; Sun, X.; Qu, J. Identification and Classification of Solid–Liquid Flow Patterns in Deviated and Horizontal Annuli. *Nat. Gas Ind. B* **2025**, *12*, 386–404. [CrossRef]
20. Gao, D.-L.; Huang, W.-J. A Review of Down-Hole Tubular String Buckling in Well Engineering. *Pet. Sci.* **2015**, *12*, 443–457. [CrossRef]
21. Tan, T.; Zhang, H. A Risk Prediction Method of Pipe Sticking Accidents Due to Wellbore Uncleanness for Long Horizontal Section Wells. *J. Pet. Sci. Eng.* **2022**, *210*, 110023. [CrossRef]
22. Li, X.; Fan, Y.; Li, J.; Su, X.; Zhan, S.; Hu, G.; He, Y.; Zhang, M. Research on the Influence of a Cuttings Bed on Drill String Friction Torque in Horizontal Well Sections. *Processes* **2022**, *10*, 2061. [CrossRef]

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