Journal of Engineering Research and Technological Innovations.
[JERTI] Vol. 1, No 2, 57 - 81 (2026)
https://journals.kwasu.edu.ng/index.php/jerti ISSN: 3093-0863

A Simulation-Based Assessment of Pipe Sticking Mechanisms in Extended-Reach Wells: Case Study of Niger Delta Fields

I. E. Ihua-Maduenyi[1]*, B. B. Kinate[2], V. A. Umejuru[3]

[1,2,3]Department of Petroleum Engineering, Faculty of Engineering, Rivers State University, Nkpolu Oroworukwo, Rivers State, Nigeria

[1]isaac.ihua-maduenyi@ust.edu.ng, [2]kinate.bright@ust.edu.ng, [3]victoria.umejuru@ust.edu.ng
*Corresponding Author: isaac.ihua-maduenyi@ust.edu.ng

ABSTRACT

Stuck pipe remains a major contributor to non-productive time in drilling operations, especially within complex geological environments such as the Niger Delta. This study presents a comprehensive modelling and simulation analysis of pipe sticking tendencies using WELLPLAN, focusing on a highly deviated extended-reach well with a 17.5-inch surface hole section, 13⅜-inch casing set at intermediate depth, and an openhole interval drilled with water-based mud. The simulations incorporate actual field data, including well trajectory, casing program, drillstring configuration, formation pressure regime, and operational practices typical of Niger Delta development wells. The objective was to quantify the mechanical and hydraulic responses of the drillstring under varying operating conditions, specifically hook load, mud weight, and openhole friction factor, and to evaluate their individual and combined impacts on stuck pipe initiation. Results show that increasing hook load reduces the measured depth of the stuck point but concurrently decreases the apparent stuck weight due to elastic stretch of the drillstring, emphasizing the need to manage over-pull within safe mechanical limits. Variations in mud weight significantly affected both stuck point depth and stuck load, demonstrating the sensitivity of differential sticking to the balance between hydrostatic pressure and formation pore pressure. The openhole friction factor had a strong influence on sticking behaviour in lower-tension conditions, although its effect diminished at higher hook loads where axial stress dominates. The modelling also highlighted the importance of casing placement and hole geometry, revealing that inadequate standoff in the openhole section amplifies the potential for mechanical sticking, particularly during tripping and reaming operations. The study highlights the complex interplay among wellbore geometry, drilling-fluid properties, and operational parameters in the development of stuck pipe. The findings underscore the value of predictive simulation for optimizing drilling parameters, improving hole cleaning, guiding mud weight selection, and minimizing openhole exposure. This integrated approach provides a practical framework for reducing non-productive time and enhancing well integrity in deviated and extended-reach wells across the Niger Delta.

Keywords: Differential sticking, WELLPLAN, torque and drag, hook load, mud weight

1. INTRODUCTION

The exploration and production of hydrocarbons have increasingly relied on advanced drilling technologies to access reservoirs previously considered uneconomical or technically challenging. Among these advancements, highly deviated wells and extended reach wells (ERWs) have become central to maximizing reservoir contact and optimizing hydrocarbon recovery. These well designs enable operators to reach multiple targets from a single surface location, navigate complex subsurface geometries, and minimize environmental footprints. However, as the deployment of directional and extended reach drilling expands, so do the operational, mechanical, and geological complexities associated with these wells. A critical challenge in such complex trajectories is pipe sticking, a persistent and costly issue in drilling operations globally (Zhao et al., 2022; Zhu et al., 2022). Pipe sticking occurs when the drill string becomes immobilized within the wellbore, preventing either further drilling or retrieval of the bottom-hole assembly (BHA). Such events significantly disrupt

Publisher
Faculty of Engineering and Technology,
Kwara State University, Malete. P.M.B. 1530 Ilorin,
Kwara State, Nigeria.

https://doi.org/10.5281/zenodo.21512063

drilling operations, often requiring time-consuming and expensive interventions, including jarring, back-reaming, fishing, sidetracking, or, in extreme cases, abandoning the well. Stuck pipe incidents account for a substantial proportion of non-productive time (NPT), with studies reporting up to 25% of drilling problems in challenging formations attributable to this phenomenon (Zhao et al., 2024). The financial impact is substantial, especially in ERWs where equipment costs, operational complexity, and logistical challenges amplify the consequences of a single sticking event.

The risk of pipe sticking increases in highly deviated and extended reach trajectories due to increased contact between the drill string and the wellbore wall, which elevates both drag and torque. Horizontal or near-horizontal sections further complicate cuttings transport, fluid circulation, and mechanical standoff, making these sections prone to differential sticking, cuttings accumulation, and keyseating (Peng et al., 2025; Zhu et al., 2021; Ma et al., 2022; Huque et al., 2021). Mechanically, drill string immobilization may result from inadequate hole cleaning, ledges, sloughing shales, or other wellbore irregularities. Differential sticking, by contrast, occurs when a portion of the drill string becomes embedded against a permeable formation under a hydrostatic pressure exceeding formation pore pressure (Tan & Zhang, 2022; Li et al., 2019). In practice, both mechanisms often coexist in ERWs, increasing the complexity of identifying root causes and implementing effective mitigation strategies.

Conventional well design approaches and empirical mitigation methods often prove inadequate in predicting and preventing pipe sticking in such challenging environments (Zhu et al., 2021; Rasul et al., 2020). Consequently, operators increasingly rely on sophisticated simulation tools such as WELLPLAN, which provides integrated modules for torque and drag analysis, hydraulics modeling, surge and swab prediction, and mechanical integrity assessment. By combining physics-based numerical modeling with real-time data, WELLPLAN enables predictive assessment of drilling dysfunctions, including sticking tendencies, and allows engineers to optimize drilling parameters virtually before field implementation (Tang et al., 2021; Chen et al., 2022; Al-Rubaii et al., 2023). The predictive capability of simulation-based approaches offers a cost-effective and risk-reducing alternative to reactive measures traditionally used in stuck pipe mitigation.

In extended reach and highly deviated wells, the simulation of pipe sticking requires a comprehensive assessment of parameters such as dogleg severity, wellbore geometry, annular cuttings load, drill string configuration, friction factors, and real-time wellbore pressure conditions. Torque and drag analysis quantifies normal and lateral contact forces along the wellbore, while hydraulics modeling assesses cuttings transport efficiency and equivalent circulating density management both critical for preventing mechanical and differential sticking (Tang et al., 2022; Zhao et al., 2022; Ofei & Yaaqob, 2019). Case-specific geological and operational data further enhance simulation fidelity, improving the predictive reliability of stuck pipe risk models.

Field applications of WELLPLAN have demonstrated its utility in minimizing stuck pipe events across diverse environments. For instance, pre-drill simulations in the North Sea and offshore West Africa have guided optimal BHA design, fluid selection, and trajectory modification to reduce sticking risk. Land-based ERWs in the Middle East and China have benefited from simulation-based adjustments in tripping speed, flow rate, and weight-on-bit (WOB) management, resulting in significant reductions in NPT and operational costs (Ma et al., 2022; An et al., 2023; Chen et al., 2022). Despite these successes, the accuracy and applicability of simulation outputs depend heavily on input data quality, modeling assumptions, and a comprehensive understanding of subsurface conditions.

Given the growing reliance on ERWs, particularly in deepwater and marginal fields, the importance of proactive stuck pipe prevention through advanced simulation cannot be overstated (Boukredera et al., 2022; van Oort et al., 2021). The combination of long horizontal sections, complex lithologies, high-pressure/high-temperature conditions, and tight operational margins necessitates a shift from reactive remediation to predictive, model-driven planning. This study, therefore, leverages WELLPLAN simulations to model the mechanical and hydraulic behavior of the drill string in highly deviated wellbores, evaluate the influence of operational and wellbore parameters on pipe sticking, and provide actionable insights to enhance operational efficiency and reduce NPT in Niger Delta drilling environments.

While previous WELLPLAN-based investigations have generally addressed cuttings transport, torque-and-drag behaviour, or sticking risk in extended-reach wells as isolated phenomena, the novelty of the present study lies in its integrated, case-specific evaluation of mechanical and differential sticking mechanisms within a single Niger Delta extended-reach well. Specifically, this work simultaneously quantifies the individual and combined sensitivities of hook load, mud weight, and openhole friction factor on both the measured depth and apparent weight of the stuck point, using field-validated trajectory, casing, and drillstring data rather than generic or synthetic well geometries. By coupling torque-and-drag diagnostics (effective tension, side force, buckling, and stretch) with dedicated stuck-pipe simulation outputs, the study provides a unified, field-applicable framework, rather than a purely theoretical treatment, for anticipating and mitigating stuck-pipe risk in Niger Delta extended-reach drilling, an environment for which such integrated simulation-based evidence remains comparatively limited in the literature.

2. PIPE STICKING IN EXTENDED REACH WELLS

Pipe sticking remains one of the most challenging and economically significant problems in drilling operations, particularly in highly deviated and extended reach wells (ERWs). These wells, characterized by long horizontal departures and complex trajectories, expose the drill string to increased frictional contact, torque, and drag forces, which collectively elevate the risk of immobilization (Zhao et al., 2022; Zhu et al., 2022; Baldino & Ozbayoglu, 2025). Stuck pipe incidents not only disrupt drilling operations but also result in substantial non-productive time (NPT), financial loss, and increased safety hazards. In ERWs, the severity of sticking is amplified by geometric complexity, reduced buoyancy, inefficient cuttings transport, and wellbore instability, making proactive prediction and mitigation strategies essential (Omomo et al., 2024; Livescu & Craig, 2017; Al-Rubaii et al., 2023).

2.1 Origin and Classification of Pipe Sticking

Pipe sticking occurs when the drill string becomes immobilized within the wellbore, preventing further drilling or retrieval of the bottom-hole assembly without intervention (Chen et al., 2022). The origins of pipe sticking are multifactorial, stemming from mechanical, hydraulic, and formation-related causes. In ERWs, prolonged horizontal exposure, gravitational sag, and extended contact with the borehole wall exacerbate these risks. Pipe sticking is broadly classified into mechanical sticking and differential sticking (Ma et al., 2022; Zhao et al., 2022; Tan & Zhang, 2022).

Mechanical sticking arises from physical obstruction of the drill string, often due to cuttings accumulation, borehole collapse, keyseating, or geometric restrictions in the wellbore. This type is more prevalent in highly deviated wells, where the drill string naturally gravitates toward the low side of the borehole, increasing contact forces and frictional resistance (Zhu et al., 2022; Peng et al., 2025).

Differential sticking, on the other hand, is a pressure-induced phenomenon. It occurs when the hydrostatic pressure in the wellbore exceeds formation pore pressure, forcing the pipe against a permeable formation wall. The resultant net force pins the pipe, particularly during static periods such as tripping or connections. Differential sticking is typically associated with vertical or near-vertical wells, but in ERWs, the increased pipe-wall contact area makes even deviated sections susceptible (Huque et al., 2021; Ma et al., 2022; Li et al., 2019).

Hybrid or compound sticking conditions often occur in practice, where mechanical and differential mechanisms interact. For example, a pipe initially held by cuttings accumulation may subsequently experience differential sticking due to overbalance pressure, creating complex release challenges (Zhu & Zhang, 2017; Livescu & Craig, 2018).

2.2 Mechanical Pipe Sticking in Extended Reach Wells

Mechanical sticking is particularly significant in highly deviated and ERWs, as geometric and operational factors amplify the forces acting on the drill string. As inclination increases beyond 60°, the axial component of gravitational force diminishes, resulting in higher normal forces between the drill string and the wellbore wall. In long horizontal sections, drag forces accumulate along the string, increasing surface torque and hook loads (Zhao et al., 2022; Baldino & Ozbayoglu, 2025).

Hole cleaning inefficiency is a dominant contributor. Reduced annular velocity and laminar flow in horizontal sections promote cuttings deposition, forming beds that can mechanically trap the pipe. Compaction of these cuttings under axial weight creates resistant zones that may persist even under applied tension (Zhu et al., 2022; Rasul et al., 2020; Huque et al., 2021). Keyseating is another critical mechanism, occurring when tool joints or stabilizers cut narrow grooves into the borehole wall under repeated lateral forces, often during sliding operations. These grooves can entrap larger BHA components, particularly when the well trajectory includes doglegs or abrupt directional changes (Livescu & Craig, 2017; Sarker et al., 2017; Zhu et al., 2017).

Borehole instability also contributes to mechanical sticking. Shale sloughing, washouts, or formation collapse introduce debris that can obstruct the pipe, particularly in ERWs with extended horizontal exposure. Improper tripping practices such as rapid pipe movement or inadequate circulation can exacerbate mechanical sticking by inducing swab and surge pressures that mobilize cuttings into bridging configurations (Sarker et al., 2017; An et al., 2023). Mechanical sticking is further influenced by operational factors, including weight-on-bit, rotational speed, torque, and dogleg severity. High dogleg severity increases bending stresses and contact pressure, intensifying the potential for keyseating and pack-off, while excessive tripping speeds or poor torque management elevate side forces and friction (Ma et al., 2022; Tan et al., 2022; Ofei & Yaaqob, 2019; Yeung et al., 2017).

2.3 Fundamentals of Modelling and Simulation of Pipe Sticking

Accurate prediction of pipe sticking requires both analytical and numerical modeling approaches. Analytical models quantify axial and lateral forces, torque, drag, and critical points of buckling using simplified assumptions about well geometry, pipe stiffness, and friction. Mechanical sticking is typically modeled as a flexible beam subjected to distributed forces along the trajectory, while differential sticking models calculate contact force based on hydrostatic overbalance, contact area, and filter cake properties (Zhao et al., 2022; Ma et al., 2022; Li et al., 2019). While analytical methods provide valuable preliminary insights and sensitivity analysis, they often fail to capture the nonlinearities of real-world ERWs.

Numerical simulation, particularly using WELLPLAN, offers a robust solution for complex well configurations. WELLPLAN integrates torque and drag analysis, hydraulics, surge and swab effects, and mechanical wellbore modeling to simulate both mechanical and differential sticking under dynamic operational conditions (Tang et al., 2021; Chen et al., 2022; Al-Rubaii et al., 2023).

For mechanical sticking, the software discretizes the well trajectory, calculating contact angles, normal forces, and frictional resistance at each node to identify high-risk zones. Differential sticking is modeled by incorporating formation pore pressure, mud density, permeability, and filter cake characteristics to estimate the force required to mobilize the pipe (Zhao et al., 2022; Tan & Zhang, 2022; Li et al., 2019).

Advanced simulation in WELLPLAN allows for scenario analysis, including variations in tripping speed, mud weight, well trajectory, and fluid rheology. It also accounts for time-dependent phenomena such as filter cake build-up, cuttings compaction, and transient pressure fluctuations during connections or circulation stoppage (Tan & Zhang, 2022; Peng et al., 2025; An et al., 2023). These capabilities enable engineers to predict zones of elevated sticking risk, optimize operational parameters, and plan preventive strategies proactively. Real-time monitoring data, when integrated into WELLPLAN, further enhances predictive accuracy by reflecting actual downhole conditions, allowing for dynamic adjustments during drilling (Omomo et al., 2024; Al-Rubaii et al., 2023).

3. MATERIALS AND METHODS

This section presents the modeling and simulation methodology used to evaluate the mechanisms and dominant factors contributing to pipe sticking in highly deviated wells. The analysis focuses on an extended-reach well (ERW) with a complex trajectory and a total measured depth of approximately 35,017 ft. Attention is restricted to the open-hole interval, as the upper sections have been secured with conductor, surface, and intermediate casing strings.

The simulations were performed using WELLPLAN, a module within Landmark's Engineer's Desktop™ (EDT™) software suite. EDT™ is a widely adopted well construction platform that supports both pre-drill engineering and real-time drilling operations. WELLPLAN is designed to evaluate drilling and completion challenges such as stuck pipe, drillstring buckling, torque-and-drag behavior, casing wear, and mechanical lockup, making it particularly suited for extended-reach well analysis.

In this study, WELLPLAN was employed to model drillstring–wellbore interactions under realistic operational conditions. The software enables detailed characterization of how wellbore geometry, formation behavior, drilling fluid properties, and drillstring mechanics combine to influence pipe sticking. By replicating drillstring dynamics within the open-hole section, the simulations capture scenarios leading to both mechanical and differential sticking. The platform also supports sensitivity analyses, allowing systematic evaluation of key variables such as side forces, torque and drag profiles, annular pressures, and mud system characteristics.

3.1 Case Study

The case study examined in this research centers on the drilling of Well AX02, located in the Asa Field of the Niger Delta. The well is designed as an extended-reach drilling (ERD) operation, distinguished by a substantial lateral departure and a complex inclination profile. Well AX02 is planned to a total measured depth (MD) of 35,017 ft, drilled in multiple sections tailored to the casing program and formation characteristics. The primary interval of interest is the production hole, drilled with an 8½-in bit, extending approximately 22,867 ft from 12,150 ft MD to the well's final depth at 35,017 ft MD.

The upper sections of the wellbore have been systematically cased and cemented to ensure structural stability and zonal isolation. The casing program comprises a 30-in conductor casing set from surface to 400 ft MD, followed by a 13⅜-in surface casing to 6,102 ft MD, and a 9⅝-in intermediate casing set from 6,102 ft to 12,015 ft MD. This intermediate casing marks the transition into the open-hole production interval evaluated in this study.

To ensure mechanical soundness along the long and highly deviated trajectory, a torque and drag (T&D) analysis was performed. This analysis was essential for optimizing the design of the drillstring and bottom-hole assembly (BHA). Its objective was to pre-emptively identify and mitigate potential downhole mechanical issues such as helical buckling, mechanical lockup, excessive drag loads, and drillstring fatigue or failure. By modeling the anticipated mechanical responses under various operational modes including rotary drilling, sliding, and tripping, the study refined the drillstring configuration, stabilizer placement, and operational parameters.

3.1.1 Data Input

The simulation relied on a comprehensive dataset that included the following key inputs: well trajectory information (measured depth, inclination, and azimuth), hole geometry data, rig specifications (such as block weight and number of strung lines), drilling fluid properties, friction factors, pore pressure and fluid gradients, wellbore tortuosity profiles, and operational parameters. These inputs are summarized in Table 1, Table 2 and Table 3.

Table 1: General Data

S/N	Parameter	Value
1	Fluid density (base)	10.8 ppg
2	Block weight	90 kips
3	Block rating limit	1500 kips
4	Friction factors	0.2 OHFF, 0.25 OHFF and 0.3 OHFF and 0.15CHFF
5	Total Well depth	35,017 ft
6	Section of Well under investigation	From 12,015 ft to 35,017 ft
7	Reservoir temperature	220^{o}F
8	Geothermal gradient	1.74^{o}F/100ft
9	Trip speed	60 ft/min
10	Slack-off weight (sliding)	20 kips
11	Maximum yield of Overpull	90%
12	Rheological model	Herschel-Bulkley

Table 2: Hole and Casing Data

S/N	Parameter	Value
1	Conductor Pipe	30 in OD, 28.5in ID, 234ppf, runs from surface to 400ft
2	Surface Casing	13-3/8 in OD, 12.415 in ID, 68ppf, runs from 400ft to 6102 ft
3	Intermediate Casing	9-5/8 in OD, 8.535 in ID, 53.5ppf, runs from 6102 ft to 12,150 ft
4	Hole Section	8-1/2 in Hole runs from 12,150 ft to 35,017 ft

Table 3: BHA data

S/N	TYPE	LENGTH		BODY		WEIGHT
		PIPE	TOTAL	OD	ID	
		[ft]	[ft]	[in]	[in]	[lb/ft]
1	8.5" PDC Bit	1.05	1.05	6.00	2.25	85.0
2	PD 675 Orbit AA 8-1/2" Stabilized CC (8-3/8") (w.NP FV)	14.05	15.10	6.72	4.2	105.08
3	Receiver	5.29	20.39	6.86	3.125	100.80
4	EcoScope (LWD)	25.95	46.34	6.813	5.125	141.11
5	Telescope 675 NF	27.11	73.45	6.813	5.125	141.11
6	Stethoscope 675 w/8 1/4 '' Stabilizer	33.03	106.48	6.9	2.81	76.92
7	8-3/8 Reaming Stab (Bi-directional)	5.31	111.79	6.81	2.81	67.64
8	6.75" Flex NMDC	29.03	140.82	6.75	2.875	106.91
9	Float Sub (with Non-ported float valve)	2.83	143.65	6.75	2.75	117.43
10	6.75" DH Filter Sub	5.61	149.26	6.75	3.00	106.91
11	6-3/4" DAV Catcher Sub	13.11	162.37	6.75	2.75	102.73
12	6-3/4" DAV Valve Sub	6.53	168.9	6.688	2.75	102.73
13	X.O	3.72	172.62	6.87	2.75	109.82
14	3 x 5-1/2" HWDP (3 joints)	93.68	266.30	5.5	3.25	73.5
15	X/O (VF50 P x 41/2 IF B)	3.64	269.94	7.00	2.875	117.43
16	Jar	30.32	300.26	6.5	2.75	90.88
17	X/O (41/2 IF P x VF50 B)	3.84	304.10	7.00	2.875	117.43
18	9 x 5-1/2" HWDP (9 joints)	281.22	585.32	5.5	3.25	73.5
19	5-1/2" IEU x 21.9 lbs/ft VAM® X-Force TM VF50 135	31	616.32	5.5	4.778	21.90

3.1.2 Simulation

Simulating pipe-sticking phenomena in extended-reach drilling operations using WELLPLAN requires a structured, technically rigorous workflow that integrates field measurements, well trajectory geometry, operational parameters, and detailed mechanical–hydraulic modeling. The procedure begins with the acquisition, organization, and validation of all relevant drilling and subsurface data. Essential inputs include the complete directional survey—measured depth (MD), true vertical depth (TVD), inclination, and azimuth—alongside formation pressures, fracture gradients, permeability information, and the full specifications of the drillstring, BHA, bit, and casing program. These datasets establish the physical constraints and operational envelope in which the WELLPLAN simulation is executed.

The well profile is then constructed by importing or manually defining the trajectory within WELLPLAN's geometry builder. Each geometric segment, vertical, build-up, tangent, and horizontal is precisely described to preserve dogleg severity and tortuosity. This step is critical in ERD wells, where minor variations in curvature significantly influence contact forces, frictional drag, and the onset of pipe-sticking mechanisms.

Drilling fluid properties are subsequently defined with high fidelity. Inputs include mud type, density, rheological parameters (yield point, plastic viscosity, and, where applicable, power-law constants k and n), gel strengths, and temperature-dependent viscosity behavior. Accurate fluid characterization is essential because rheology and overbalance pressure govern both hydraulic performance and differential-sticking potential through filter-cake deposition and adhesion forces.

The mechanical configuration of the drillstring is then modeled in detail. WELLPLAN requires specification of pipe outer diameters, tool joint dimensions, linear weight, stiffness characteristics, and connection types, as well as the layout of BHA components such as drill collars, heavyweight drill pipe, stabilizers, and jars. Segmenting the string along its length enables localized calculations of axial load, buckling tendency, and side forces. Friction coefficients for cased and open-hole intervals are incorporated based on field measurements or empirical correlations. Additional inputs such as overbalance pressure, filter-cake thickness, and assumed contact area support the differential-sticking calculations.

Operational scenarios are then defined for three primary modes of drilling activity: rotary drilling, sliding, and tripping. Each mode presents distinct mechanical responses and pipe-sticking risks. Continuous rotation during rotary drilling tends to reduce differential sticking but increases torque and drag. Sliding operations promote elevated side forces due to static pipe–wall contact, increasing the

likelihood of mechanical sticking. Tripping particularly when conducted without circulation introduces the highest sensitivity to cuttings accumulation, surge/swab pressures, and static differential-pressure sticking. Scenario-specific parameters such as ROP, tripping speed, RPM, flow rate, and pump characteristics are specified within WELLPLAN's operational modules.

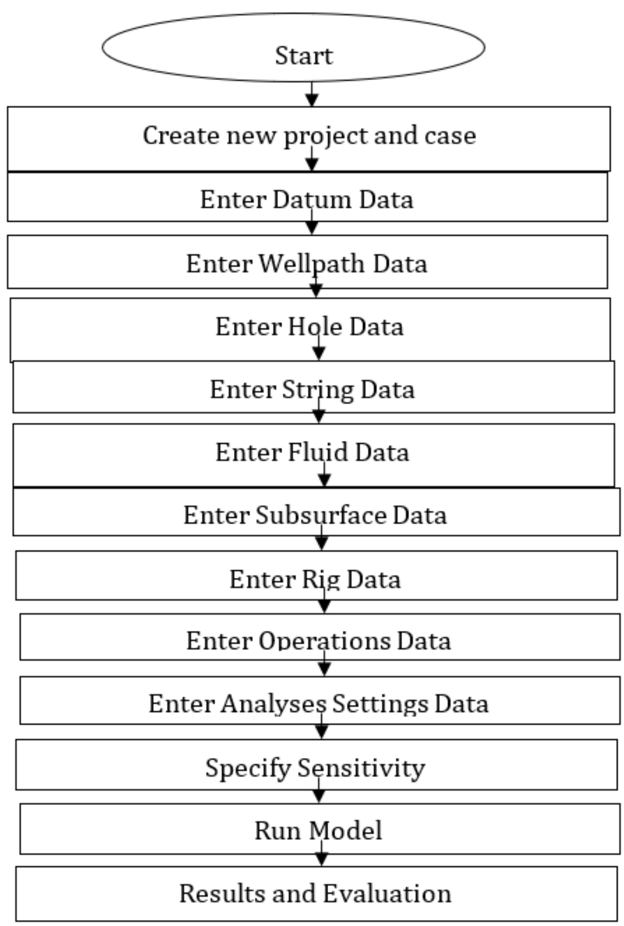
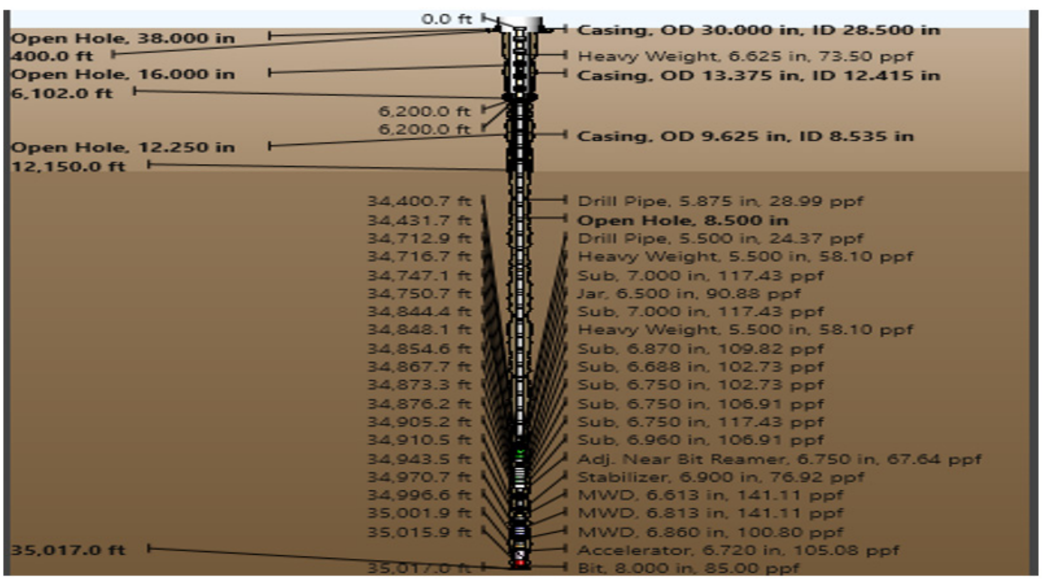


Figure 1: Pipe sticking modeling flowchart in WellPlan

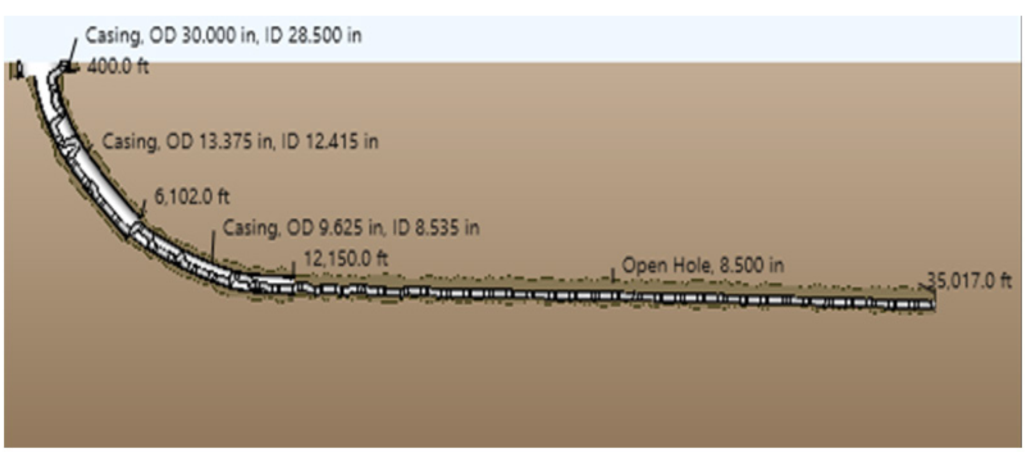
Once all inputs are defined, the simulation is executed using WELLPLAN's Torque & Drag and Hydraulics engines. The T&D module computes axial load, torque, side forces, and effective tension along the drillstring, identifying zones where compressive or lateral loads exceed safe mechanical thresholds. Differential-sticking calculations estimate sticking forces based on the interaction between overbalance pressure, filter-cake adhesion, and pipe contact conditions. For trip-induced pressure effects, the Swab/Surge module simulates transient downhole pressures, highlighting regions susceptible to overbalance- or underbalance-induced sticking.

Sensitivity analyses are conducted by varying key parameters such as mud weight, tripping velocity, pipe rotation, and friction factors to assess their influence on torque, drag, and sticking-force predictions. WELLPLAN's visualization tools allow direct comparison of multiple scenarios through charts, tables, and depth-dependent profiles. Outputs such as hookload curves, axial load distributions, torque plots, and differential-sticking force profiles support the identification of high-risk intervals and the evaluation of operational conditions most likely to trigger pipe-sticking events.

The flowchart of the simulation in wellplan is given in Figure 1.



a) Strings/BHA schematics in the hole



b) 3D well schematics

Figure 2: Strings/BHA schematics and well schematics

4. RESULTS AND DISCUSSION

4.1 Results of Torque and Drag Parameters Affecting Pipe Sticking

This section presents the results and discussion derived from the modeling and simulation of pipe-sticking behavior in a highly deviated well. The analysis, performed using the WELLPLAN software, focuses on the principal mechanical parameters that govern pipe-sticking risk effective tension, hookload, drag, torque, side force, buckling tendency, and axial stretch. These outputs are evaluated not only within the context of conventional torque-and-drag behavior but, more critically, in relation to the mechanisms that lead to pipe immobilization. The results highlight the depths, operational modes, and loading conditions most susceptible to stuck-pipe events in the studied extended-reach well. Mechanical responses were evaluated for multiple operational scenarios, including tripping in, tripping out, rotating on bottom, and sliding. The computed values of effective tension, hookload, drag, torque, side forces, buckling indicators, and drillstring stretch were generated using a stiff-string modeling approach, which was selected due to the well's significant lateral displacement and complex trajectory. For long, highly deviated, or extended-reach wells, the stiff-string model provides a more realistic representation of drillstring behavior than the simplified soft-string formulation, making it the most appropriate theoretical basis for this study.

4.1.1 Effective Tension and Effect on Pipe Sticking Risk

Effective tension is a critical parameter in assessing stuck-pipe susceptibility, as it reflects the net axial force distribution along the drillstring. In this analysis, effective-tension profiles were used to identify intervals where the string transitions into compression zones that signal the onset of buckling. Buckling elevates pipe–wellbore contact forces, significantly increasing frictional resistance and, consequently, the probability of mechanical sticking. The simulation results show that sliding and tripping-in generate the lowest effective-tension values, with compression extending from the bottomhole to approximately 2,742 ft. Under rotating-on-bottom (ROB) conditions, compression persists to

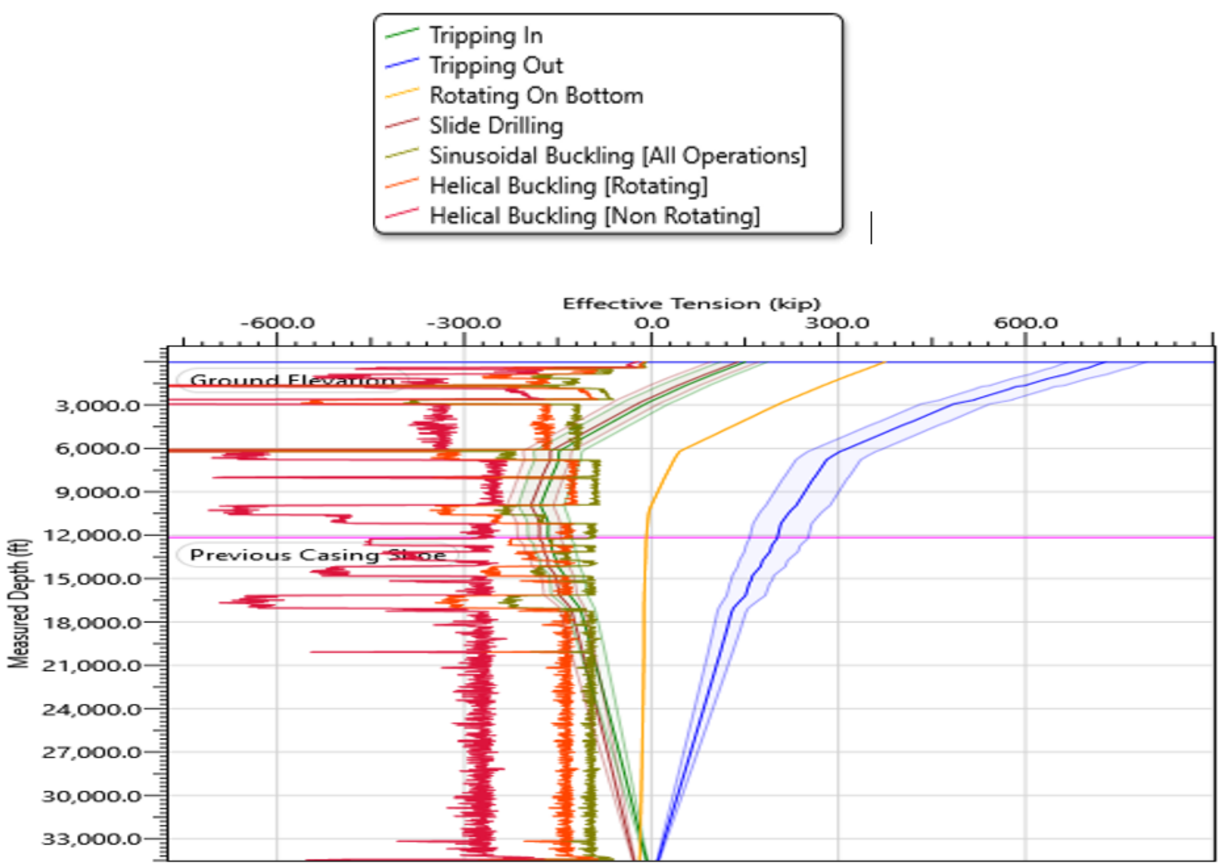


Figure 3: Effective tension for the well

about 9,950 ft, indicating a substantially larger high-risk interval. These depths represent the most critical zones in terms of stuck-pipe potential. Effective tension therefore serves as a key diagnostic parameter for evaluating buckling tendencies, optimizing drillstring and BHA design, and guiding safe operating practices. The effective-tension response of the stiff-string model for various operational modes including tripping in, tripping out, ROB, and sliding is illustrated in Figure 3.

The analysis of Figure 3 demonstrates that variations in effective tension across different operational modes have a direct influence on pipe-sticking risk in highly deviated wells. Among all evaluated conditions, tripping out produces the highest effective-tension values, while sliding operations consistently yield the lowest across the full depth range and for all openhole friction factors (OHFFs). The elevated tension observed during tripping out is advantageous, as higher axial tensile loads keep the drillstring fully stretched, minimize pipe–wellbore contact, and reduce the likelihood of both mechanical and differential sticking. Under these conditions, the entire drillstring remains in tension from bottomhole to surface, significantly lowering stuck-pipe susceptibility. In contrast, sliding operations present the greatest risk. The imposition of a 20-kip slack-off weight induces substantial compressive forces along the lower section of the string, lowering effective tension and pushing large portions of the drillstring into compression. This compression promotes the onset of sinusoidal and helical buckling, which increases pipe–wall contact pressure and frictional resistance. Elevated contact forces heighten the potential for cuttings bed formation, inefficient hole cleaning, and localized differential sticking risks that are especially pronounced in deviated and horizontal intervals where side forces are inherently higher.

Rotating-on-bottom (ROB) also exhibits reduced effective tension due to the transmission of weight on bit (WOB) into the drillstring. This compressive load propagates upward and results in compression from bottomhole to approximately 9,950 ft, indicating an extended interval where buckling may occur. Although pipe rotation can help mitigate differential pressure sticking by disturbing static contact points, the presence of compression across such a broad interval increases drag, torque, and the likelihood of cuttings bed formation, all of which elevate the probability of mechanical sticking. Both tripping in and sliding show compression in the interval extending from bottomhole to roughly 2,742 ft, marking a critical risk zone for stuck pipe. Compressed regions are inherently more susceptible to buckling and increased pipe-wall interaction, making these operations more sensitive to poor hole cleaning and elevated friction.

The trends summarized in Table 4 confirm that higher OHFF values intensify compression during tripping in and sliding, thereby further reducing effective tension. This indicates that in wells with inadequate hole cleaning, elevated drag, or adverse frictional conditions, the likelihood of stuck pipe during these operations increases significantly.

Table 4: Comparison of Effective tension at the surface for stiff string and soft string models

	Effective Tension at Surface, kips		
Operations	**0.2**	**0.25**	**0.3**
Tripping in	187.4	151.4	111.3
Tripping out	669.8	729.1	795.3
Rotating On Bottom	355.7	355.7	355.7
Sliding	172.9	139.7	95.1

Building on the interpretation of Figure 4, further analysis of Table 4 indicates that the relationship between friction factor and effective tension is highly operation-dependent and strongly influenced by the orientation of drag forces. During tripping-in and sliding operations, increases in friction factor lead to a consistent reduction in surface effective tension for both soft-string and stiff-string configurations. This occurs because the drag force, which scales with friction factor, acts downward along the string, opposing tensile loads. As a result, effective tension decreases, promoting compressive stresses along the string. From a pipe-sticking perspective, this trend is significant, as reduced effective tension and increased compressive loading elevate the likelihood of sinusoidal and helical buckling, higher pipe-to-wellbore contact forces, and cuttings bed entrapment, all key contributors to mechanical sticking in highly deviated wells. Conversely, during tripping-out operations, drag forces act in a positive orientation as the string is pulled upward, thereby augmenting effective tension at the surface. In this case, higher friction factors enhance bottomhole tension, maintaining the string in a more stretched condition and reducing the propensity for buckling or mechanical sticking. Although increased friction may result in higher overpull at the surface, the overall risk of stuck pipe during tripping out is generally lower than during tripping in or sliding.

For rotating-on-bottom (ROB) operations, effective tension appears relatively insensitive to variations in friction factor. This reflects the dominant influence of weight on bit and hydraulic forces in controlling axial loads, with friction manifesting more as torque than as changes in tension. Nevertheless, sticking risks in ROB remain, primarily associated with increased torque, lateral forces, and compromised hole cleaning. Elevated friction due to poor cuttings removal or thick filter cake can still lead to differential or mechanical sticking, despite nominal changes in axial tension.

4.1.2 Hook Load and Effect on Pipe Sticking Risk

The Hookload represents the total load acting on the drillstring and rig substructure, effectively reflecting the combined weight of the string during operations such as tripping in, tripping out, rotating on bottom (ROB), and sliding. Unlike effective tension, which is calculated progressively from the bottomhole to the surface, Hookload is measured from the surface downward, providing a direct indicator of the loads experienced by the rig equipment. Figure 4 presents the Hookload response for the stiff-string model used in the simulations.

Hookload trends are particularly significant in the context of pipe-sticking, as sudden or abnormal deviations from expected values often serve as the first surface-level indications of impending or active sticking events. For example, during tripping out, an unexpected increase in Hookload may indicate excessive drag or cuttings accumulation along the wellbore, both of which can lead to mechanical sticking. Conversely, during tripping in, a lower-than-anticipated Hookload may signal reduced string mobility due to high frictional resistance or localized differential sticking in permeable zones. Similarly, during ROB operations, persistent fluctuations or erratic Hookload patterns can be associated with poor hole cleaning or buckling, both of which increase pipe-to-wall contact and the risk of sticking.

By comparing observed Hookload profiles with model predictions for various operations, anomalies can be detected as early warnings of potential sticking. Consequently, Hookload serves as a critical monitoring parameter for stuck-pipe analysis, providing surface-measurable evidence of subsurface frictional and mechanical behavior that cannot be directly observed downhole.

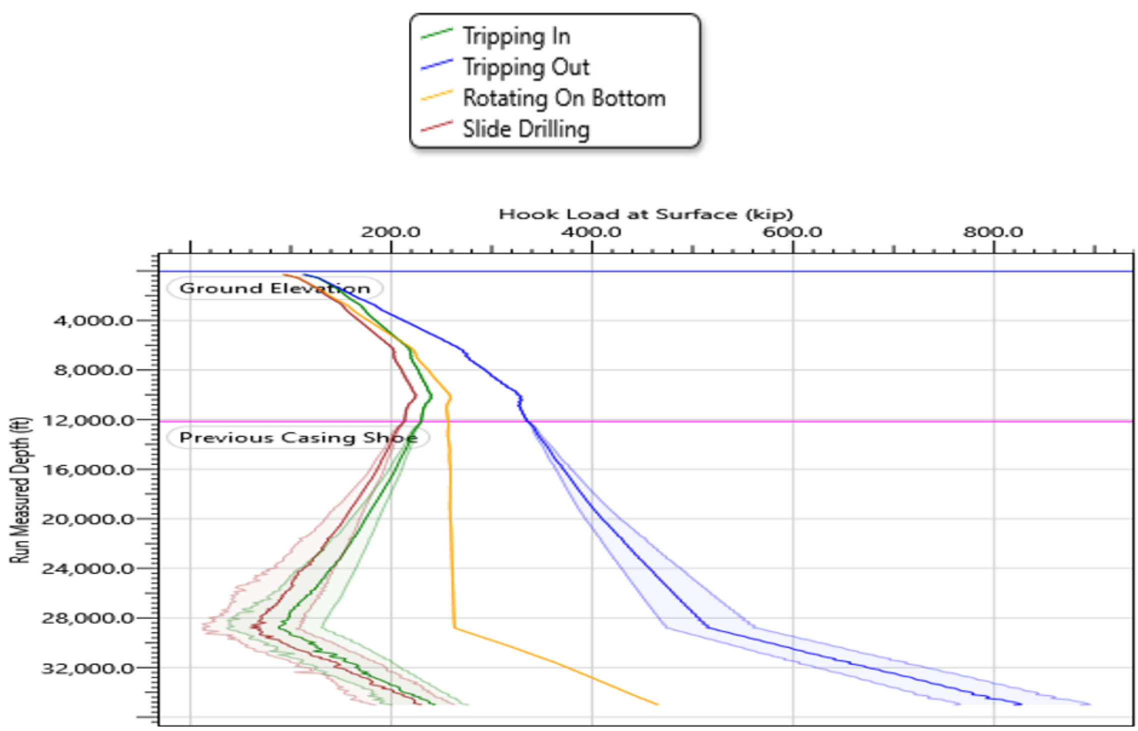


Figure 4: Hook loads for stiff string model

Figure 4 illustrates the Hookload (HL) response for the stiff-string model across four operational modes, tripping in, tripping out, rotating on bottom (ROB), and sliding under varying open-hole friction factors (0.20, 0.25, and 0.30 OHFF) while maintaining a constant cased-hole friction factor (0.15 CHFF). The results demonstrate distinct HL trends dependent on both the type of operation and the applied friction factor. Tripping out consistently produces the highest HL, reflecting the additional tensile forces required to overcome gravity and frictional drag. ROB operations exhibit intermediate HL values, whereas tripping in and sliding display comparatively lower HLs due to the predominance of compressive and negative drag forces acting on the string.

From a pipe-sticking perspective, these HL trends are highly informative. Elevated HL during tripping out is expected; however, anomalous increases beyond predicted levels may indicate cuttings accumulation, differential sticking, or severe drag along deviated wellbore sections. Conversely, during tripping in or sliding, abnormally low HL relative to model predictions can signal loss of string mobility due to high frictional resistance, borehole contact, or localized sticking tendencies. In this analysis, the strings were successfully run to bottom depth across all operations and friction factors without evidence of lockup or string failure, suggesting that sticking risks were effectively managed under the simulated conditions.

The observed variations in HL with changing friction factors provide further insight into the mechanisms leading to pipe sticking. Higher OHFF values increase the drag component of HL, thereby elevating the risk of mechanical sticking in extended-reach or highly deviated intervals. Additionally, discrepancies between modeled HL (as summarized in Table 5) and field-observed HL can serve as early warning signals for potential stuck-pipe conditions. Consequently, continuous monitoring of HL is essential both for verifying safe string deployment and for real-time identification of developing sticking risks.

Table 5: Bottom Hook loads

	Bottom Hook loads, kips		
Operations	**0.2OHFF**	**0.25OHFF**	**0.3OHFF**
Tripping in	277.4	241.4	201.3
Tripping out	759.8	819.1	885.3
Rotating On Bottom	445.7	445.7	445.7
Sliding	262.9	229.7	185.1

Building on the observations from Figure 5, Table 5 further clarifies how friction factor influences the Hookload (HL) across different operations and string models. For tripping in and sliding operations, an increase in friction factor results in a reduction in bottom HL for both soft-string and stiff-string models. This outcome is explained by the orientation of the drag force: during downward movements such as tripping in and sliding, drag acts in a negative direction. As friction factor increases, the negative drag subtracts from the total string weight, thereby reducing the net HL.

In contrast, during tripping out, the drag force acts positively as the string is pulled upward against gravity. Under these conditions, increasing the friction factor raises the drag force, which is added to the total string weight, resulting in higher HL values. Rotating on-bottom (ROB) operations, however, show no variation in HL with friction factor, since drag forces are neutralized by continuous rotation, leaving the HL constant across the tested scenarios.

From a pipe-sticking perspective, these HL behaviors are highly relevant. During tripping in and sliding, reduced HL values with increasing friction factor indicate a growing resistance to string movement, even though the surface load appears smaller. This "masked" reduction in HL can conceal significant downhole contact forces and localized sticking tendencies, particularly in highly deviated sections where the pipe is forced against the borehole wall. On the other hand, the higher HL observed during tripping out under increasing friction conditions may be interpreted as a warning signal: excessive HL values could suggest developing cuttings beds, differential sticking forces, or mechanical restriction zones along the wellbore.

The constancy of HL during ROB operations should not be misconstrued as an absence of sticking risk. While HL remains unchanged, side forces and torque may rise substantially with friction factor, creating conditions favorable for differential sticking and mechanical lock-up.

Therefore, the variations in HL highlighted by Table 5 emphasize that tripping in and sliding operations are more susceptible to hidden sticking risks due to reduced HL, while tripping out presents risks detectable as abnormal HL increases. ROB operations, though showing constant HL, require additional monitoring of torque and side forces to fully capture pipe sticking potential. This makes HL interpretation, when considered alongside other parameters, a vital diagnostic tool for anticipating and preventing stuck pipe events.

4.1.3 Drag and Effect on Pipe Sticking Risk

The calculation of drag accounts for the combined effects of friction and normal forces acting between the drillstring and the wellbore. Because drag is directly proportional to the normal force, any increase in contact pressure along the borehole wall amplifies the resistance experienced by the string. In practice, drag is evaluated in two primary forms: pickup (PU) drag and slack-off (SO) drag. PU drag corresponds to the additional frictional resistance encountered during pulling-out-of-hole (POOH) operations, whereas SO drag represents the resistance experienced during running-in-hole (RIH). Typically, PU drag exceeds SO drag, as lifting the string requires overcoming both its weight and frictional resistance, while gravity assists the downward motion during RIH, partially offsetting frictional effects. Figure 5 illustrates these trends for the stiff-string simulation model.

Drag serves as a critical indicator of potential pipe-sticking risk. Excessive PU drag during POOH may indicate cuttings accumulation, differential sticking zones, or mechanical restrictions, all of which can escalate to partial or complete sticking if unaddressed. Similarly, abnormal increases in SO drag during RIH reflect heightened frictional resistance, suggesting that the pipe is being pressed against the borehole wall—particularly in deviated sections where side forces are significant. These conditions can contribute to mechanical sticking, especially if circulation is insufficient to remove cuttings or in tight-hole sections.

Monitoring drag trends therefore provides an early warning of developing stuck-pipe tendencies. A growing disparity between PU and SO drag beyond expected model predictions is particularly significant, as it may indicate progressive borehole deterioration, formation swelling, or cuttings buildup that could immobilize the string. In this way, drag functions not only as a frictional load calculation but also as a practical diagnostic tool for predicting and preventing stuck-pipe events.

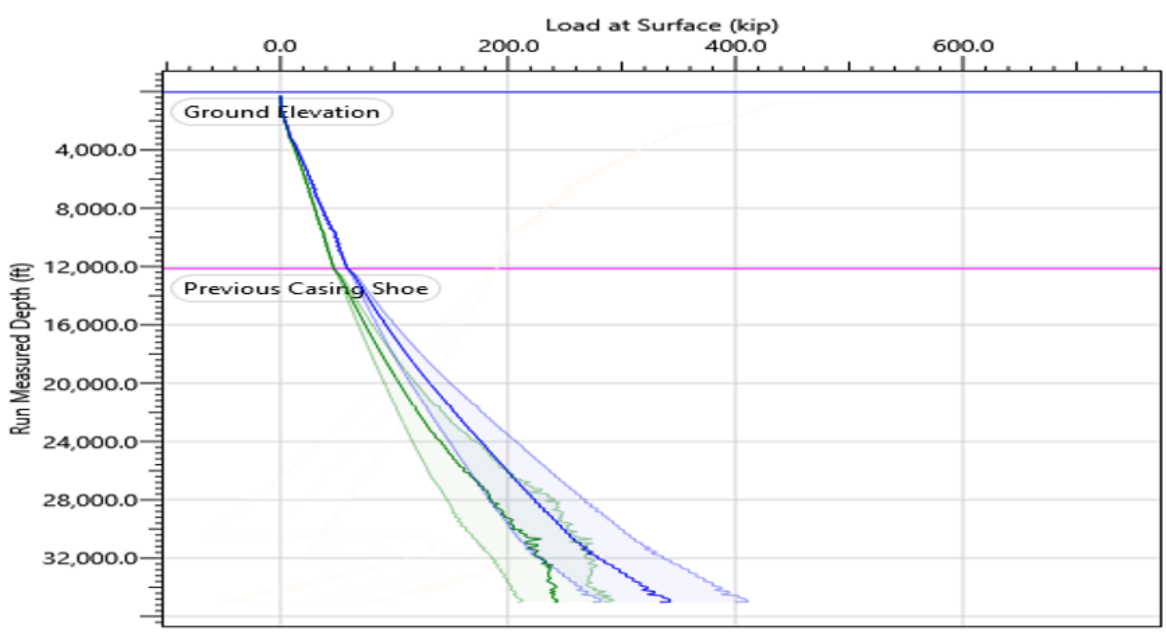


Figure 5: PU and SO drag plot

Observations from Figure 5 show that both pickup (PU) and slack-off (SO) drag increase progressively with depth, reflecting the cumulative effect of frictional forces along the wellbore. As expected, PU drag consistently exceeds SO drag, primarily because pulling the string out of the hole (POOH) requires overcoming both its weight and additional frictional resistance. Conversely, during running-in-hole (RIH), gravity assists the downward movement, resulting in comparatively lower SO drag. The disparity between PU and SO drag becomes more pronounced with increasing depth and higher friction factors, highlighting the growing influence of friction in deeper or more deviated sections. Table 6 presents the bottom drag values for the string under the various operations and friction factor scenarios considered.

In the context of pipe-sticking risk, these drag trends are particularly informative. The steady increase in PU drag with depth may indicate greater resistance due to cuttings accumulation, inadequate hole cleaning, or excessive side forces, all of which elevate the likelihood of mechanical sticking during POOH operations. Similarly, increases in SO drag at greater depths, although smaller in magnitude, reflect higher frictional contact between the pipe and the borehole wall during RIH, creating conditions conducive to differential sticking, especially in permeable or high-pressure zones.

The widening gap between PU and SO drag with depth serves as an early warning of deteriorating wellbore conditions. Such divergence may signal escalating cuttings buildup, borehole instability, or formation swelling, each of which increases the risk of string immobilization if corrective measures such as enhanced circulation, reaming, or friction reduction—are not implemented. Therefore, careful monitoring of PU and SO drag, particularly their depth-dependent divergence, is essential for anticipating and mitigating stuck-pipe events in highly deviated wells.

Table 6: Bottom drag results

	Bottom Drag, kips		
Operation	**0.2**	**0.25**	**0.3**
SO	208.3	244.2	284.4
PU	274.1	333.5	399.6

Table 6 demonstrates that both slack-off (SO) and pickup (PU) drag increase as the openhole friction factor (OHFF) rises from 0.2 to 0.3, illustrating the direct influence of friction factor on drag forces along the drillstring. Across all friction factors, PU drag consistently exceeds SO drag, aligning with theoretical expectations: pulling the string out of the hole requires overcoming both the gravitational load and frictional resistance, whereas running the string in benefits from gravity, which partially offsets friction.

From a pipe-sticking perspective, these trends are particularly important. The increase in drag with higher OHFF indicates that deteriorating wellbore conditions—such as rough surfaces, cuttings accumulation, or keyseating intensify frictional resistance and raise the likelihood of mechanical sticking. The consistently higher PU drag further emphasizes that POOH operations are more susceptible to sticking, as excessive resistance can immobilize the string when encountering cuttings beds or tight spots. Conversely, while SO drag is generally lower, abnormal increases during RIH may signal problematic frictional contact or swelling formations, which could contribute to differential sticking.

Overall, the relationship between friction factor and drag not only confirms theoretical expectations but also underscores the importance of drag monitoring as a diagnostic tool. Identifying abnormal drag increases or an unusually large gap between PU and SO drag provides an early warning of hazardous downhole conditions, enabling proactive mitigation to prevent stuck-pipe incidents.

4.1.4 Torque and Effect on Pipe Sticking Risk

Figure 6 shows the simulated torque response during rotating-on-bottom (ROB) operations across all investigated friction factors. Torque is a key parameter for assessing pipe-sticking risk, as abnormal or elevated torque often serves as an early indicator of potential sticking events. During ROB, increased torque may result from poor hole cleaning, cuttings accumulation, or excessive side forces caused by wellbore deviation, all of which intensify pipe-to-wall contact and promote mechanical sticking. Sudden spikes in torque can also indicate localized restrictions or tight spots along the wellbore, where the drillstring is at risk of immobilization.

Monitoring torque alongside drag and Hookload provides a more comprehensive understanding of downhole conditions. While drag quantifies axial frictional resistance and Hookload reflects vertical loading, torque specifically captures rotational resistance, making it an essential parameter for diagnosing stuck-pipe tendencies during drilling. Accordingly, the simulated torque behavior in Figure 6 not only confirms the influence of friction on drilling mechanics but also serves as a predictive tool for identifying and mitigating sticking risks in highly deviated wellbores.

Observations from Figure 6 indicate that torque accumulation originates at the bit, located at the bottom of the wellbore, and progressively increases toward the surface. The torque applied at the bit remains constant at 2,000 ft-lb across all friction factors, representing the energy required to crush and penetrate the formation. However, frictional losses along the wellbore necessitate additional torque at the surface, supplied by the rotary table, to maintain this constant bit torque.

The results further demonstrate that the required surface torque is highly sensitive to the openhole friction factor (OHFF). For OHFF values of 0.2, 0.25, and 0.3, the surface torque needed to sustain the 2,000 ft-lb bit torque for the stiff-string torque and drag model is 63,180.5 ft-lb, 71,863 ft-lb, and 80,545.4 ft-lb, respectively. This trend reflects a straightforward mechanism: higher friction factors increase pipe-to-wall contact and rotational resistance, thereby requiring greater surface-applied torque to overcome the additional energy losses.

In terms of pipe-sticking risk, these findings are highly relevant. Progressive increases in surface torque with depth and OHFF suggest deteriorating wellbore conditions, including cuttings accumulation, ledges, or differential sticking zones. Excessive torque often serves as an early indicator of localized restrictions or tight spots that impede string rotation. If such conditions are not addressed, they may escalate into mechanical sticking, particularly in highly deviated sections where side forces and frictional contact are intensified.

Consequently, torque profiles provide not only a measure of the mechanical energy required for drilling but also a diagnostic tool for anticipating potential pipe-sticking events. Abnormal torque escalation, especially when observed alongside elevated drag or Hookload readings, should be interpreted as a warning signal, prompting corrective measures such as enhanced circulation to remove cuttings, reaming, or the application of lubricants to reduce friction.

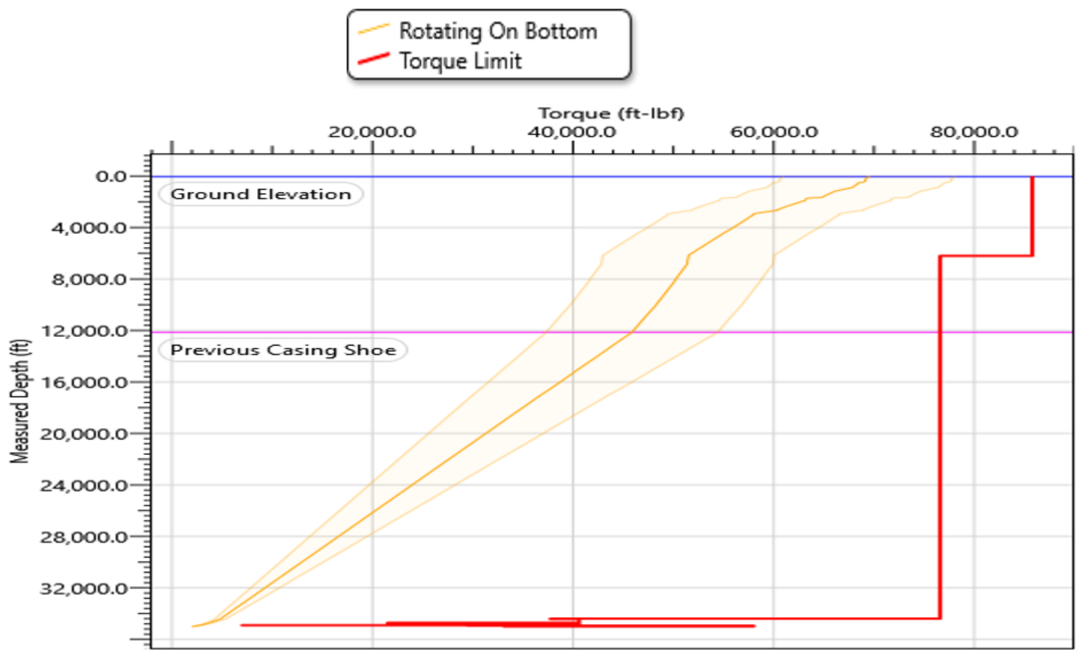


Figure 6: Torque results

4.1.5 Side Force/ Normalization Length and Effect on Pipe Sticking Risk

Figure 7 illustrates the side force/normalized length for the stiff string model simulation. Side force is a critical parameter because it represents the magnitude of lateral contact between the drillstring and the wellbore wall. High side forces identify regions where the string is pressed harder against the formation, increasing the risk of mechanical interaction with the borehole wall. Such conditions are often associated with well trajectories exhibiting high dogleg severities, where curvature forces intensify string-to-wall contact.

In relation to pipe sticking, high side forces directly contribute to sticking tendencies. Greater lateral contact increases frictional resistance during both axial and rotational movements of the string, making it more difficult to pull out, run in, or rotate the pipe. In extreme cases, this frictional resistance may immobilize the string, particularly in deviated or horizontal sections where gravity further amplifies side-loading. Additionally, zones of elevated side force are more prone to cuttings accumulation, differential sticking, and localized wear, all of which compound the risk of stuck pipe.

Therefore, the side force profile from Figure 7 is not only important for assessing buckling risks but also serves as an indicator of potential sticking zones. Identifying sections with high side force enables proactive measures, such as trajectory smoothing, optimized drilling parameters, or the use of lubricants, to minimize contact and reduce the likelihood of stuck pipe incidents.

Analysis of side force distributions in the early sections of the wellbore reveals significant operational variability, underscoring their importance in assessing pipe-sticking risks. Evaluating side forces at critical casing shoe locations provides valuable insight into zones of elevated lateral contact between the drillstring and the wellbore, which are often precursors to mechanical sticking. For the stiff-string model at an openhole friction factor (OHFF) of 0.3, side forces per unit length near the conductor shoe (417 ft) were 254, 3,978, 1,467, and 181 lbf/ft for tripping in, tripping out, rotating-on-bottom (ROB), and sliding operations, respectively. At the surface casing shoe, these values increased substantially to 202, 809, 6,007, and 4,858 lbf/ft, while the intermediate casing shoe recorded 756, 743, 643, and 894 lbf/ft, respectively, across the same operations.

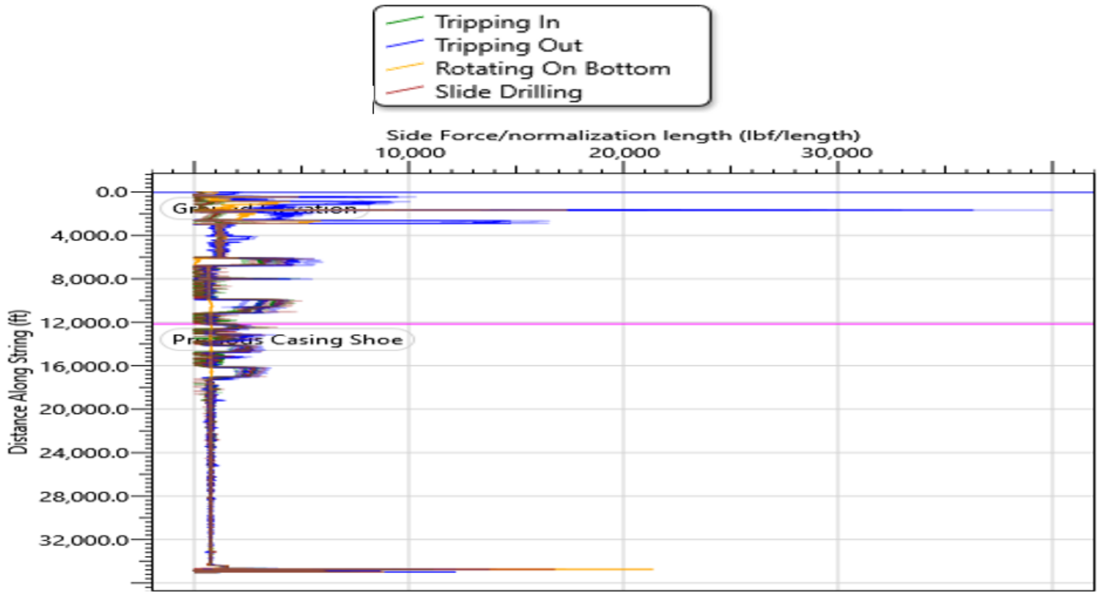


Figure 7: Side force/Normalization length

From both theoretical and field perspectives, these magnitudes highlight critical operational considerations. In shallow intervals, particularly near the conductor and surface casing shoes, the extremely high side forces during ROB (6,007 lbf/ft) and sliding (4,858 lbf/ft) are indicative of intense pipe–wellbore wall contact. In practice, such conditions are commonly associated with increased frictional resistance, localized pipe lockup, cuttings accumulation, and potential embedment of the drillstring into filter cake or wellbore irregularities. Field experience further shows that even tripping-out operations, despite being dominated by axial tension, can generate appreciable lateral forces that, when combined with differential sticking conditions, elevate the likelihood of stuck-pipe incidents.

4.1.6 Buckling and Effect on Pipe Sticking Risk

The assessment of buckling is a fundamental aspect of torque and drag analysis, given its direct impact on pipe sticking, drilling operability, and overall well integrity. Buckling induces non-linear deformation in the drillstring, which increases localized contact with the wellbore wall, thereby amplifying drag and side forces and enhancing the likelihood of differential sticking. Two primary forms of buckling are generally observed: sinusoidal and helical. Sinusoidal buckling typically occurs first and can be partially tolerated during operations; however, it reduces effective string mobility and elevates friction. Helical buckling is more severe, producing continuous pipe–wall contact, significantly altering stress distribution, restricting axial movement, and potentially immobilizing the string, leading to high-probability stuck-pipe scenarios.

In this study, buckling was systematically evaluated across different operational modes and friction factors, with effective tension profiles serving as the diagnostic tool. Effective tension plots identify locations where axial compressive forces exceed the critical threshold for buckling initiation. When effective tension drops below this threshold, sinusoidal buckling occurs, and further reduction leads to helical buckling. These phenomena were most prominent during tripping-in and sliding operations, where compressive forces dominate. The analysis further indicated that higher openhole friction factors (OHFF) accelerate the reduction in effective tension, intensifying both the onset and severity of buckling.

The implications for pipe sticking are significant. Sinusoidal buckling, while partially manageable, increases localized drag, reduces string predictability, and heightens the risk of mechanical sticking. Helical buckling constitutes a critical failure state by maximizing wall contact, restricting axial movement, and creating conditions that are highly prone to stuck-pipe events. Table 7 provides a comprehensive summary of the buckling behavior under various operational scenarios and friction factors, offering a practical framework for identifying sections of the wellbore most susceptible to pipe-sticking hazards.

Observations from Table 7 indicate that sinusoidal buckling occurred during tripping-in and sliding

Table 7: Buckling summary at 0.3OHFF

Operation	String	Depth, ft	type
	Drill pipe	6,800 to 9,920	Sinusoidal
	Drill pipe	11,210 to 14,150	Sinusoidal
	Drill pipe	14,840 to16,130	Sinusoidal
	Drill pipe	17,270 to 18,110	Sinusoidal
Tripping in	Drill pipe	18,260 to 20,030	Sinusoidal
	Drill pipe	6,800 to 7,940	Sinusoidal
	Drill pipe	8,060 to 9,920	Sinusoidal
	Drill pipe	10,610 to14,150	Sinusoidal
Sliding	Drill pipe	14,840 to 16,130	Sinusoidal
	Drill pipe	17,270 to 22,460	Sinusoidal

operations, whereas no buckling was detected during tripping-out or rotating-on-bottom (ROB) operations across all examined friction factors. Sinusoidal buckling was particularly observed in the 5 7/8-inch drill pipe at specific depth intervals during both tripping-in and sliding. Although classified as tolerable, sinusoidal buckling remains highly relevant to pipe-sticking risk. This form of buckling increases lateral displacement of the drill pipe against the wellbore wall, thereby elevating contact forces and drag resistance. Such localized wall contact enhances the probability of mechanical sticking, especially in highly deviated or tortuous well sections. Moreover, under high-friction conditions, persistent sinusoidal buckling can escalate into helical buckling, which represents a critical risk due to continuous pipe–wall contact and potential immobilization of the string.

Therefore, while the sinusoidal buckling observed in this study did not immediately compromise string deployment to the planned depth, it signals a heightened susceptibility to stuck-pipe events. This risk is further amplified in the presence of adverse wellbore conditions such as high dogleg severity, inadequate hole cleaning, or elevated openhole friction factors. Continuous monitoring of effective tension profiles, combined with proactive drag management strategies, is essential to prevent the progression of sinusoidal buckling into a full-scale stuck-pipe incident.

4.1.7 Stretch in Strings/BHA and Effect on Pipe Sticking Risk

Table 8 presents a comparison of individual and combined drillstring and bottom hole assembly (BHA) stretches across varying friction factors. These deformations classified as mechanical, ballooning, and thermal stretches —arise from stress-induced responses to downhole forces acting along the string. Each type of stretch contributes to the overall axial displacement and alters the stress distribution within the drillstring, with direct implications for pipe-sticking risk.

Mechanical stretch, governed by applied loads and effective tension, determines the extent to which the drillstring elongates or contracts under operational forces. Ballooning stretch, induced by variations in internal and external pressures, modifies the contact pressure between the pipe and wellbore wall. In permeable zones with high mud overbalance, this effect can increase the likelihood of differential sticking by embedding the pipe into the formation. Thermal stretch, caused by temperature gradients along the wellbore, introduces non-uniform expansions and contractions that can generate localized high-stress points, further exacerbating sticking tendencies.

The combined influence of these deformations becomes increasingly significant as friction factors rise. Higher friction amplifies variability in stretch responses, distorting load transfer, drag behavior, and side-force distributions along the wellbore. In highly deviated intervals, where both mechanical and contact forces are magnified, these distortions heighten the susceptibility of the drillstring to stuck-pipe events.

The stretch data in Table 8 shows that drillstring deformations though often secondary to tension, drag, and torque considerations play a critical role in the development of stuck-pipe conditions. Effective monitoring and management of mechanical, ballooning, and thermal stretches are therefore essential to mitigate risks, particularly under prolonged static conditions, elevated friction factors, and complex well geometries.

Table 8 summarizes the mechanical, ballooning, and thermal stretches of the drillstring and bottom hole assembly (BHA) under the influence of torque and drag, comparing outcomes for both soft-string and stiff-string

Table 8: Stretch analyses of strings in torque and drag

Operation	Friction Factor	Mechanical	Ballooning	Thermal	Total
	0.2	-14.2	2.8	3.3	-8.1
	0.25	-17.4	2.8	3.3	-11.3
Tripping in	0.3	-20.6	2.8	3.3	-14.5
	0.2	12.7	2.8	3.3	18.8
	0.25	16.3	2.8	3.3	22.4
Tripping out	0.3	20.2	2.8	3.3	26.3
	0.2	-3.7	2.8	3.3	2.4
	0.25	-3.7	2.8	3.3	2.4
ROB	0.3	-3.7	2.8	3.3	2.4
	0.2	-16.7	2.8	3.3	-10.6
	0.25	-19.8	2.8	3.3	-13.7
Sliding	0.3	-23	2.8	3.3	-16.9

models. Positive values indicate string elongation, while negative values reflect shortening. The results show that mechanical stretch is strongly dependent on the openhole friction factor (OHFF), increasing with higher friction values, whereas ballooning and thermal stretches remain relatively constant across all friction factors and operational modes.

Operationally, tripping-in, sliding, and rotating on-bottom (ROB) consistently produced net shortening of the string, while tripping-out induced elongation. These variations have direct implications for pipe-sticking risk, as they affect string–wellbore contact, drag forces, and stress distribution along the string. Shortening during tripping-in or sliding promotes compressive loads, which can intensify buckling tendencies and increase localized pipe–wall contact, thereby elevating the probability of mechanical sticking. Conversely, elongation during tripping-out reduces compressive stress but may exacerbate frictional lock in high-dogleg or tight sections, where increased drag can resist upward motion and trigger stuck-pipe events.

The significance of stretch analysis extends beyond axial load assessment. Accurate evaluation of mechanical, ballooning, and thermal stretches is critical for maintaining string integrity and BHA stability. Underestimation or miscalculation of stretch can lead to improper tool lapping, unintended stress concentrations, or disengagement of BHA components, all of which increase the risk of immobilization and compromise well integrity. Consequently, careful monitoring and management of stretch under varying loads and friction conditions is essential, as it represents a subtle but important factor in the onset of stuck-pipe events.

4.2 Results of Analyses of Stuck Pipe

This section presents the results of stuck-pipe modeling and simulation conducted using Wellplan software. The simulations were designed to evaluate the influence of key drilling and wellbore parameters including final hook load, mud weight, friction factor, and drillstring stretch on the occurrence and severity of stuck-pipe events. Each parameter is first introduced in terms of its operational significance, followed by a comprehensive discussion of the simulation outcomes and their implications for pipe-sticking behavior. The analysis is supported by the corresponding figures generated from the simulations, providing a detailed and quantitative assessment of the mechanisms contributing to stuck-pipe risks.

4.2.1 Effect of Final Hook Load

The hook load represents the surface load measured at the rig hook while supporting the drillstring, reflecting the total suspended weight of the string in air after accounting for buoyancy effects from the drilling fluid. In the event of a stuck pipe, the final hook load indicates the effective load transmitted to the rig system. Variations in this parameter influence both the location of the stuck point and the apparent weight of the string, making it a key diagnostic metric in Wellplan-based stuck-pipe analyses.

Figure 8 illustrates the relationship between the measured depth of the stuck point and the final hook load. The results indicate an inverse relationship, whereby the measured depth of the stuck point decreases as the final hook load increases. This behavior is consistent with expectations, as higher hook loads impose greater tensile stress on the drillstring, effectively reducing the depth at

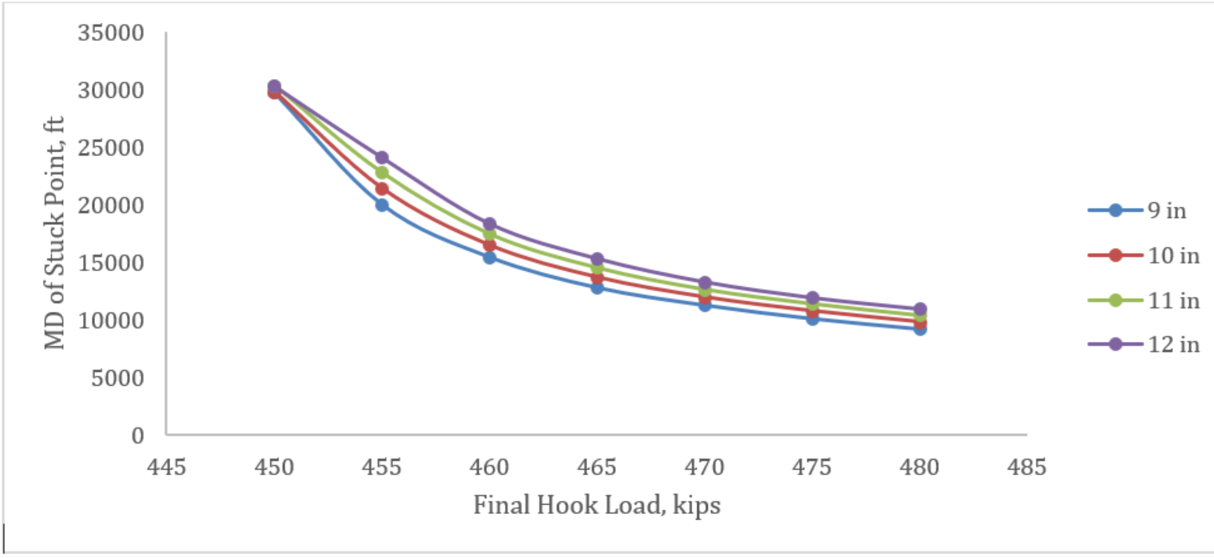


Figure 8: Stuck point vs Final Hook load

which the string becomes embedded or immobilized in the wellbore.

Conversely, for a constant final hook load, the depth of the stuck point increases with increasing string stretch. This reflects the elastic elongation of the drillstring under axial tension, which allows additional displacement before the string fully engages with the formation or encounters frictional resistance.

From an operational perspective, these trends have direct implications for stuck-pipe management. During tripping-out operations, maintaining sufficient hook load is critical to minimizing the risk of deep embedment, as higher tensile forces help mobilize the string and reduce the effective stuck depth. Conversely, monitoring drillstring stretch provides insight into tension distribution and the potential for delayed engagement with tight spots or differential sticking zones. Together, the interplay between hook load and stretch informs optimal tripping speeds, tension management, and the application of friction-reducing measures to prevent or mitigate stuck-pipe events in highly deviated wells.

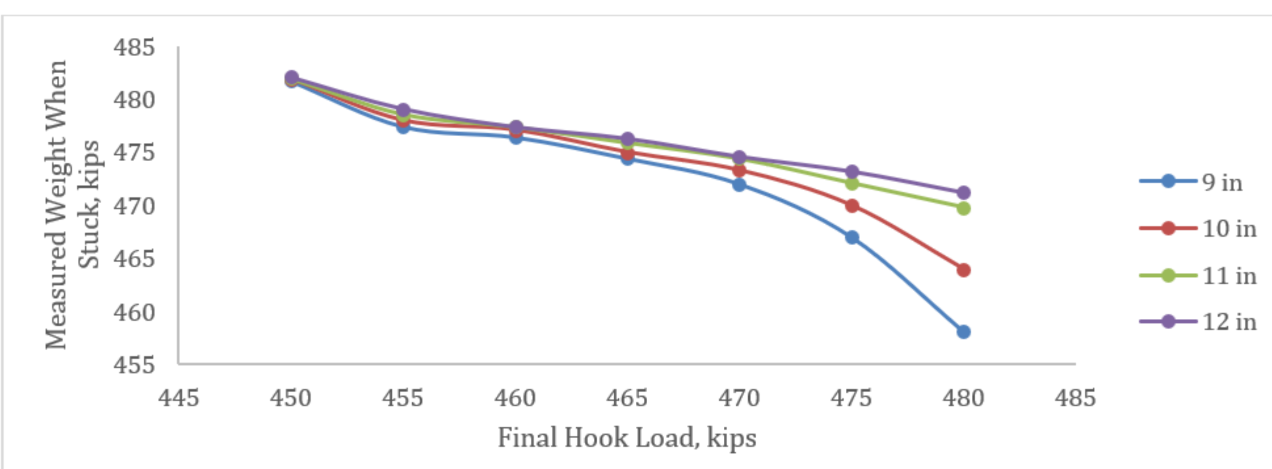


Figure 9: effect of final hook load on the measured weigh of strings when stuck

Figure 9 illustrates the influence of final hook load on the measured weight of the drillstring at the stuck point. The results demonstrate that, across all levels of string stretch, the measured weight of the stuck string decreases as the final hook load increases. This trend indicates that higher hook loads help to mobilize the string, effectively reducing the apparent stuck weight experienced at the surface.

Conversely, at higher stretch values, the measured weight of the stuck string increases, reflecting the contribution of elastic elongation of the drillstring to the effective load at the stuck point. This interplay between hook load, string stretch, and measured weight underscores the importance of tension management: while applying sufficient hook load can facilitate string movement and minimize the depth or severity of sticking, excessive over-pull in high-stretch conditions may introduce mechanical overstressing. Such overstressing can exacerbate localized friction, elevate drag forces, or even damage the string or bottom hole assembly, thereby increasing the risk of a stuck-pipe event.

Operationally, these findings highlight the need for careful balance between applied hook load and the elastic characteristics of the drillstring. Monitoring both surface load and drillstring elongation during tripping or rotation allows for optimized tension application, minimizing the likelihood of mechanical sticking while avoiding over-pull that could compromise string integrity or wellbore stability.

4.2.2 Effect of Mud Weight

Mud weight, measured in pounds per gallon (ppg), represents the density of the drilling fluid used to counterbalance formation pressures. It directly affects the hydrostatic pressure, the buoyant support of the drillstring, and the ability to transport cuttings. In the context of stuck-pipe analysis, mud weight is a critical parameter, as both excessively high and low densities can compromise borehole stability and increase the risk of differential sticking.

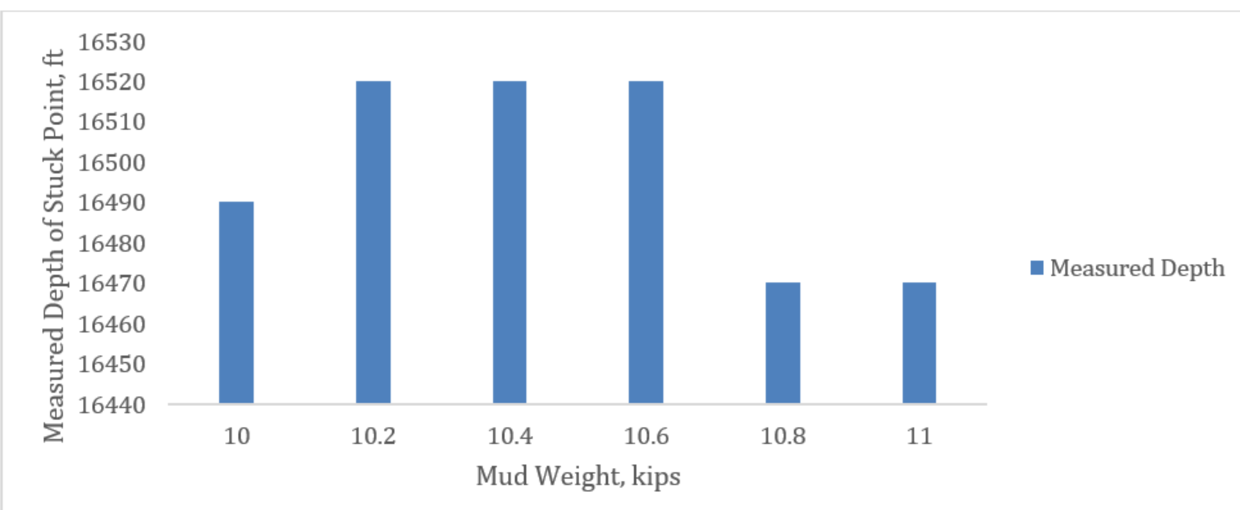


Figure 10: Mud weight vs measured weight of stuck point

Figure 10 illustrates the relationship between mud weight and the measured depth of the stuck point. The results indicate a non-linear response: as mud weight increases from 10.0 to 11.0 ppg, the depth of the stuck point initially increases, remains relatively constant between 10.2 and 10.6 ppg, and then decreases between 10.6 and 10.8 ppg, stabilizing at 11.0 ppg.

This trend reflects the competing effects of buoyancy and differential pressure on the drillstring. At lower mud weights, insufficient hydrostatic overbalance reduces buoyant support, allowing cuttings to accumulate and increasing the likelihood of mechanical sticking. In the intermediate range (10.2–10.6 ppg), the balance between hydrostatic pressure and wellbore stability maintains a relatively constant stuck depth. At higher mud weights, the elevated hydrostatic pressure promotes filter cake compaction against the borehole wall, intensifying differential sticking forces and reducing the depth at which the string can be mobilized.

Operationally, these findings highlight the critical role of mud weight management in preventing stuck-pipe events. Maintaining an optimal mud weight is essential:

too low, and the string risks mechanical lockup from insufficient buoyant support; too high, and differential sticking becomes dominant due to increased wall cake adhesion. Careful monitoring and adjustment of mud density, in conjunction with circulation practices and hole cleaning, can therefore mitigate stuck-pipe risks while preserving wellbore stability and drillstring integrity.

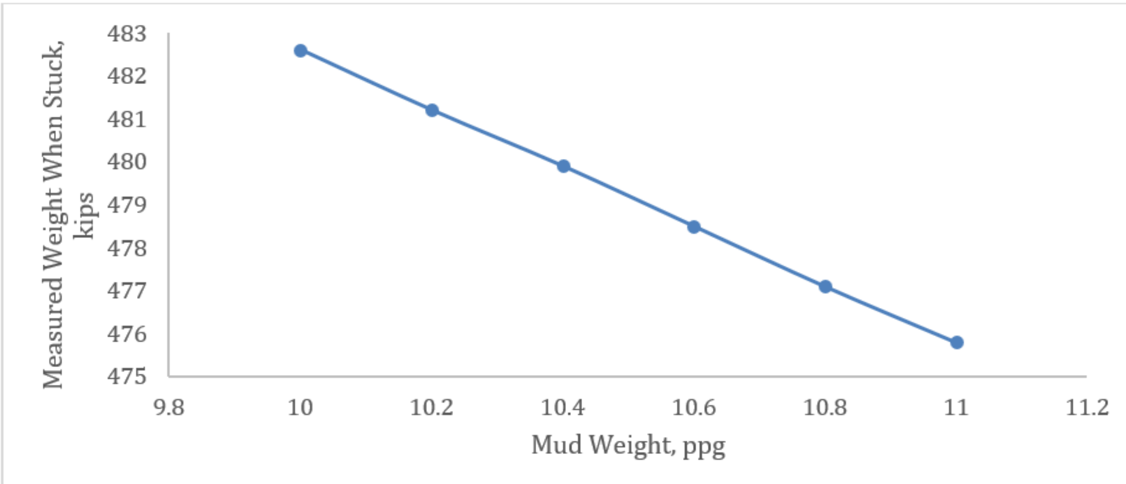


Figure 11: Effect of mud weight on measured weight when stuck

Figure 11 illustrates the influence of mud weight on the measured weight of the drillstring at the stuck point. The results show a slight decrease in the apparent stuck weight, from 16,490.2 ft to 16,470.1 ft, as mud weight increases from 10 to 11 ppg. This trend reflects the effect of buoyancy: denser drilling fluids provide greater upward support to the drillstring, effectively reducing the load transmitted to the stuck point.

However, while higher mud weight reduces the effective string weight and can facilitate mobilization, it also increases hydrostatic pressure, which promotes filter cake compaction and intensifies differential sticking in permeable or weak zones. Consequently, excessively high mud densities may paradoxically elevate the risk of stuck pipe, particularly in sections where the formation is prone to cake adhesion or swelling.

From an operational standpoint, these results emphasize the importance of mud weight optimization. Maintaining an appropriate mud density is essential to balance the benefits of buoyancy against the risks of differential sticking. Careful selection of mud weight, combined with proactive circulation and hole cleaning practices, can reduce the apparent stuck weight while minimizing the likelihood of immobilization due to formation interaction, thereby improving drillstring operability and overall wellbore safety.

4.2.3 Effect of Friction Factor on Stuck Pipe

The openhole friction factor (OHFF) quantifies the resistance encountered by the drillstring as it moves axially along the borehole wall. It is a key parameter in stuck-pipe analysis, as elevated friction increases drag forces and can impede string movement, potentially leading to immobilization. Friction factor values are affected by factors such as borehole geometry, the characteristics of the mud cake, and the condition of the drillstring surface.

Figure 12 illustrates the influence of the openhole friction factor (OHFF) on the measured depth of the stuck point. The results show that at lower final hook loads, increasing OHFF reduces the depth at which the drillstring becomes stuck, indicating that higher friction accelerates the onset of sticking by impeding axial movement along the borehole. This behavior underscores the critical role of friction in restricting string mobility, particularly in deviated or tortuous well sections where pipe-to-wall contact is more pronounced.

However, as the final hook load is increased, the effect of OHFF diminishes, with the measured stuck depth converging toward constant values. This suggests that sufficient over-pull can partially overcome frictional resistance, enabling the drillstring to reach greater depths before becoming immobilized. While this strategy may temporarily mitigate sticking, it introduces higher mechanical stresses on the drillstring and bottom hole

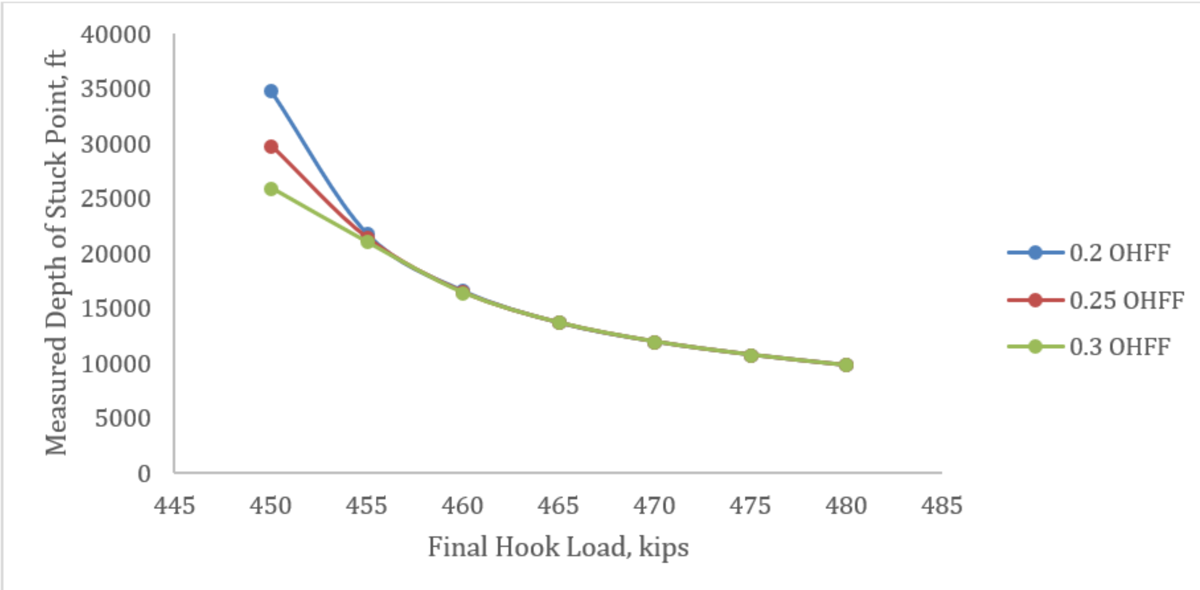


Figure 12: Effect of OHFF on the measured depth of stuck point

assembly, increasing the risk of tool fatigue, elongation, or buckling.

From an operational perspective, these findings highlight the need to carefully balance applied hook load against frictional conditions. Managing OHFF through proper hole cleaning, lubrication, and drillstring centralization can reduce frictional resistance, thereby minimizing the risk of premature sticking without relying solely on excessive over-pull, which may compromise drillstring integrity.

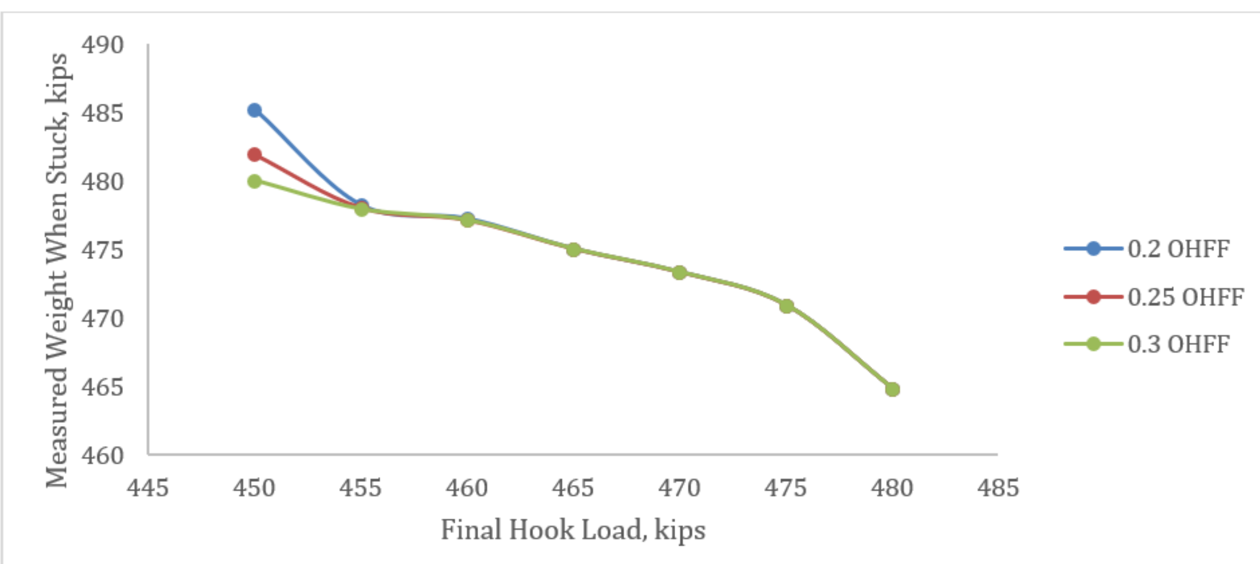


Figure 13: Effect of OHFF on the measured weight when stuck

Figure 13 illustrates the impact of the openhole friction factor (OHFF) on the measured weight of the drillstring at the stuck point. At lower hook loads, increasing OHFF results in a reduction of the measured stuck weight, reflecting the tendency of elevated friction to impede axial movement and arrest the string. Conversely, at higher hook loads, the differences in measured stuck weight diminish, indicating that sufficient over-pull can partially overcome frictional resistance.

However, relying solely on excessive hook load to mitigate sticking is inherently risky, as it can generate stresses that exceed the mechanical limits of the drillstring or bottom hole assembly, potentially causing deformation, buckling, or failure before the stuck pipe is freed. This underscores the importance of managing friction through operational measures such as proper hole cleaning, lubrication, and string centralization, rather than depending exclusively on over-pull.

4.3 Comparison with Previous Studies

The trends obtained in this study are broadly consistent with, and extend, observations reported in earlier WELLPLAN- and torque-and-drag-based investigations of extended-reach and highly deviated wells. The finding that sliding and tripping-in generate the lowest effective tension and the most extensive compression zones, thereby elevating susceptibility to sinusoidal and helical buckling, mirrors the conclusions of Zhao et al. (2022) and Baldino & Ozbayoglu (2025), who similarly identified static or low-rotation operations as the principal drivers of buckling-induced wall contact in ERWs. Likewise, the inverse relationship observed between final hook load and the measured depth of the stuck point agrees qualitatively with the modified maximum-extension and stuck-pipe prediction frameworks of Li et al. (2019), in which increasing tensile loading was also shown to reduce the depth of pipe embedment, albeit at the expense of greater drillstring stretch and mechanical stress, a trade-off this study quantifies explicitly through the combined hook load-stretch-stuck weight analysis.

The non-linear sensitivity of stuck-point depth to mud weight reported here also corroborates the differential-sticking risk framework of Tan & Zhang (2022), who showed that the balance between hydrostatic overbalance and formation pore pressure, rather than mud weight in isolation, governs the severity of pipe embedment in long horizontal and deviated sections; the present results extend this by demonstrating a comparable non-monotonic response specifically for a Niger Delta extended-reach geometry. Similarly, the diminishing influence of openhole friction factor at higher hook loads is consistent with the cuttings-bed and contact-force analyses of Ma et al. (2022) and Peng et al. (2025), which attribute the moderation of frictional effects under elevated axial tension to the dominance of axial stress over lateral wall contact once the string is sufficiently stretched. The side-force magnitudes computed near the casing shoes in this study, particularly the markedly elevated values during rotating-on-bottom and sliding operations, also align with the keyseating and contact-force mechanisms described by Huque et al. (2021) and Sarker et al. (2017), reinforcing the view that shallow, low-tension intervals remain disproportionately vulnerable to mechanical sticking even in wells where the bulk of the trajectory is adequately managed.

Taken together, these comparisons indicate that while the qualitative mechanisms identified in this study, buckling under compression, differential sticking under hydrostatic overbalance, and friction-moderated stuck-point migration, are consistent with the wider literature on extended-reach drilling, the case-specific, field-data-driven quantification provided here (e.g., depth-resolved side forces at casing shoe locations, combined hook load-stretch-stuck weight relationships, and friction-factor-dependent surface torque requirements) offers an added layer of operational specificity that is less commonly reported for Niger Delta wells. This strengthens the practical value of the present findings for guiding mud weight selection, hook load management, and friction mitigation strategies in similar ERW developments.

5. CONCLUSION

The Wellplan simulations of stuck pipe scenarios in Niger Delta drilling environments have provided a comprehensive understanding of the factors influencing pipe sticking and the complex interplay between mechanical, hydraulic, and frictional forces. The study demonstrates that hook load, mud weight, and friction factor are key parameters controlling the onset, severity, and location of stuck pipe events. Increasing final hook load was shown to reduce the measured depth of stuck points while decreasing the apparent stuck weight. However, excessive over-pull introduces higher drillstring stretch and mechanical stresses, highlighting the need for careful management to avoid exacerbating the risk of drillstring failure.

Mud weight emerged as a critical factor influencing both the measured depth and weight of stuck pipe. While higher mud densities improve buoyancy and reduce apparent stuck weight, they simultaneously increase the potential for differential sticking, particularly in permeable zones or high-pressure formations. Maintaining mud weight within an optimal operational window is therefore essential to balance borehole stability against the risk of pipe immobilization.

Frictional resistance, represented by the openhole friction factor (OHFF), significantly affects axial and rotational string behavior. At lower hook loads, higher

OHFF values increase drag and reduce the depth at which the pipe becomes stuck, whereas at higher hook loads, frictional effects are partially overcome at the expense of elevated mechanical stresses. This underscores the importance of understanding frictional interactions between the drillstring and the wellbore, particularly in highly deviated or tortuous sections where lateral side forces and buckling may develop.

The simulations further revealed the relevance of string stretch, torque, drag, side forces, and buckling phenomena in diagnosing potential sticking points. Tripping in and sliding operations are most susceptible to sinusoidal and helical buckling, as compressive forces and lateral wall contact increase with depth and friction factor. Drag and side-force distributions provide early indicators of areas prone to mechanical sticking, while torque measurements during rotating-on-bottom operations highlight rotational resistance that can exacerbate pipe immobilization. Stretch effects—, including mechanical, ballooning, and thermal deformations —also influence load distribution along the string and the bottom hole assembly, affecting both operational safety and the likelihood of stuck pipe.

Overall, this study emphasizes the interconnectedness of mechanical loads, drilling fluid design, and frictional behavior in controlling stuck pipe risks. By integrating predictive simulation with operational monitoring, drilling engineers can identify critical zones, optimize mud weight, manage hook load and stretch, and proactively adjust parameters to minimize the risk of pipe sticking. These findings provide a robust framework for anticipating and mitigating stuck pipe events, enhancing operational efficiency, and preserving well integrity in Niger Delta and similar challenging drilling environments.

Acknowledgments

We sincerely acknowledge the Department of Petroleum Engineering in Rivers State University, Rivers State, Nigeria and all individuals who played a part in the accomplishment of this research project.

Conflicting Interests

There was no conflict of interest.

REFERENCES

Al-Rubaii, M., Al-Shargabi, M., & Al-Shehri, D. (2023). A novel automated model for evaluation of the efficiency of hole cleaning conditions during drilling operations. Applied Sciences, 13(11), 6464. https://doi.org/10.3390/app13116464

An, J., Li, J., Huang, H., Liu, G., Yang, H., Zhang, G., & Chen, S. (2023). Transient cutting transport model for horizontal wells with a slim hole. Energy Science & Engineering, 11(2), 796-810. https://doi.org/10.1002/ese3.1363

Baldino, S., & Ozbayoglu, E. (2025, February). Quantifying the Impact of Cuttings and Fluid Properties on Friction Coefficient in Torque & Drag Analysis. In SPE/IADC Drilling Conference and Exhibition (p. D011S005R006). SPE. https://doi.org/10.2118/223671-MS

Boukredera, F. S., Hadjadj, A., & Youcefi, M. R. (2022). Drill string torsional vibrations modeling with dynamic drill pipe properties measurement and field validation. Journal of Energy Resources Technology, 144(2), 024502. https://doi.org/10.1115/1.4051299

Chen, Y., Zhang, H., Li, J., Zhou, Y., Lu, Z., Ouyang, Y., & Zhang, G. (2022). Simulation study on cuttings transport of the wavy wellbore trajectory in the long horizontal wellbore. Journal of Petroleum Science and Engineering, 215, 110584. https://doi.org/10.1016/j.petrol.2022.110584

Huque, M. M., Rahman, M. A., Zendehboudi, S., Butt, S., & Imtiaz, S. (2021). Investigation of cuttings transport in a horizontal well with high-speed visualization and electrical resistance tomography technique. Journal of Natural Gas Science and Engineering, 92, 103968. https://doi.org/10.1016/j.jngse.2021.103968

Kingsley, N., Emuobosa, A., & Chukwuemeka, H. (2024). Hydraulic modeling and real-time optimization of drilling fluids: A future perspective. Global J Res Eng Technol, 2(2), 030-038. https://doi.org/10.58175/gjret.2024.2.2.0030

Li, X., Gao, D., Lu, B., Zeng, Y., & Zhang, J. (2019). Study on modified maximum extension length prediction model for horizontal wells considering differential sticking. Journal of Petroleum Science and Engineering, 183, 106371. https://doi.org/10.1016/j.petrol.2019.106371

Li, X., Gao, D., Lu, B., Zeng, Y., Ding, S., & Zhou, S. (2019). A prediction model of the shortest drilling time for horizontal section in extended-reach well. Journal of Petroleum Science and Engineering, 182, 106319. https://doi.org/10.1016/j.petrol.2019.106319

Livescu, S., & Craig, S. (2017). A critical review of the coiled tubing friction-reducing technologies in extended-reach wells. Part 1: Lubricants. Journal of petroleum science and engineering, 157, 747-759. https://doi.org/10.1016/j.petrol.2017.07.072

Livescu, S., & Craig, S. (2018). A critical review of the coiled tubing friction-reducing technologies in extended-reach wells. Part 2: Vibratory tools and tractors. Journal of Petroleum Science and Engineering, 166, 44-54. https://doi.org/10.1016/j.petrol.2018.03.026

Ma, L., Lai, J., Zhang, X., Wu, Z., & Tang, L. (2022). Comprehensive insight into cuttings motion characteristics in deviated and horizontal wells considering various factors via CFD simulation. Journal of Petroleum Science and Engineering, 208, 109490. https://doi.org/10.1016/j.petrol.2021.109490

Ofei, T. N., & Yaaqob, S. Y. (2019). Numerical simulation of transport behaviour of small cuttings in extended reach wells. International Journal of Oil, Gas and Coal Technology, 21(2), 149-168. https://doi.org/10.1504/IJOGCT.2019.099587

Peng, C., Xiao, Y., Fu, J., Cao, Q., Zhang, J., Su, Y., ... & Zheng, D. (2025). Numerical validation of a novel cuttings bed impeller for extended reach horizontal wells. Petroleum Research, 10(1), 105-128. https://doi.org/10.1016/j.ptlrs.2024.07.002

Rasul, G., Qureshi, M. F., Ferroudji, H., Butt, S., Hasan, R., Hassan, I., & Rahman, M. A. (2020). Analysis of cuttings transport and flow pattern in nearly horizontal extended reach well. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 71(2), 69-86. https://doi.org/10.37934/arfmts.71.2.6986

Sarker, M., Rideout, D. G., & Butt, S. D. (2017). Dynamic model for 3D motions of a horizontal oilwell BHA with wellbore stick-slip whirl interaction. Journal of Petroleum Science and Engineering, 157, 482-506. https://doi.org/10.1016/j.petrol.2017.07.025

Tan, T., & Zhang, H. (2022). A risk prediction method of pipe sticking accidents due to wellbore uncleanness for long horizontal section wells. Journal of Petroleum Science and Engineering, 210, 110023. https://doi.org/10.1016/j.petrol.2021.110023

Tang, L., Zhang, S., Zhang, X., Ma, L., & Pu, B. (2021). A review of axial vibration tool development and application for friction-reduction in extended reach wells. Journal of Petroleum Science and Engineering, 199, 108348. https://doi.org/10.1016/j.petrol.2021.108348

van Oort, E., Chen, D., Ashok, P., & Fallah, A. (2021, March). Constructing deep closed-loop geothermal wells for globally scalable energy production by leveraging oil and gas ERD and HPHT well construction expertise. In SPE/IADC Drilling Conference and Exhibition (p. D021S002R001). SPE. https://doi.org/10.2118/204097-MS

Yeung, J., Li, J., Lee, J., & Guo, X. (2017, March). Evaluation of lubricants performance for coiled tubing application in extended reach well. In SPE/ICoTA Well Intervention Conference and Exhibition (p. D021S011R007). SPE. https://doi.org/10.2118/184810-MS

Zhao, J., Huang, W., Gao, D., & Zhao, L. (2022, June). Mechanism analysis of the regular pipe sticking in extended-reach drilling in the eastern South China Sea. In ARMA US Rock Mechanics/Geomechanics Symposium (pp. ARMA-2022). ARMA. https://doi.org/10.56952/ARMA-2022-0563

Zhao, J., Huang, W., & Gao, D. (2024). Interaction between Pipe Rotation and Cuttings Transport in Extended-Reach Drilling: Mechanism, Model, and Applications. SPE Journal, 1-20. https://doi.org/10.2118/219483-PA

Zhu, X., & Zhang, Z. (2017). Design of an ultra-high torque double shoulder drill-pipe tool joint for extended reach wells. Natural Gas Industry B, 4(5), 374-381. https://doi.org/10.1016/j.ngib.2017.10.002

Zhu, N., Huang, W., & Gao, D. (2021). Dynamic wavy distribution of cuttings bed in extended reach drilling. Journal of Petroleum Science and Engineering, 198, 108171. https://doi.org/10.1016/j.petrol.2020.108171

Zhu, N., Huang, W., & Gao, D. (2022). Numerical analysis of the stuck pipe mechanism related to the cutting bed under various drilling operations. Journal of Petroleum Science and Engineering, 208, 109783. https://doi.org/10.1016/j.petrol.2021.109783

Zhu, S., Song, X., Zhu, Z., Yao, X., & Liu, M. (2022). Intelligent prediction of stuck pipe using combined data-driven and knowledge-driven model. Applied Sciences, 12(10), 5282. https://doi.org/10.3390/app12105282