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Identification and Mitigation of Stuck Pipe Problem During Cement Drill-Out Cement in XSF Well

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ABSTRACT - This study is aimed to develop an integrated diagnostic framework to identify pack-off–type stuck pipe during cement drill-out operations and strengthen quantitative risk assessment for workover interventions. A stuck pipe event in the XSF well (9-5/8-in. section) at 724.42 m was investigated using drilling data, drill-string mechanics, drilling fluid evaluation, and hydraulic/cutting-transport analysis. The results of the mechanical assessment showed that excessive loading and overpull were unlikely primary causes of stuck pipe problem. However, the hydraulic and transport evaluation showed inadequate cutting removal, consistent with particle settling and progressive pack-off formation. To evaluate this event, a diagnostic classification matrix combining four operational indicators was applied, showing complete agreement with an established pack-off classification method. The pipe was ultimately freed after 99 hours using controlled tension-cycling with spotting-fluid support. Based on the transport analysis, this study recommended operational controls, which included maintaining a minimum circulation rate of 340 GPM and the use of shale shakers during cement removal to reduce pack-off risk. Furthermore, the prolonged liberation time showed the substantial cost impact of stuck pipe problem, supporting the economic case for preventive implementation.

Keywords: pack off, stuck pipe, work on Pipe, drilling hydraulic, cutting transport, particle bed index, hydraulic transport efficiency, diagnostic framework.

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INTRODUCTION

Workover operations are conducted in the oil and gas sector to recover or enhance hydrocarbon production from existing wells. These operations constitute an integral component of well maintenance processes, comprising modifications to reservoir parameters such as cementing, relining, and stimulation (Sofyan et al., 2023). Across diverse well-intervention technologies, there is frequent occurrence of analogous challenges in particle management and mechanical restriction.

For example, Purwanto et al. (2022) reported that coiled tubing (CT) operations for frac plug milling in unconventional reservoirs showed progressive CT string fatigue, increasing 38.06% at operational depth to 43.18% near surface.

The success of these operations is significantly dependent on systematic pressure management, hydraulic parameter optimization, and adequate particle removal systems. The results show that, regardless of intervention methods like conventional drill pipe or CT, inadequate solids transport mechanisms represent a universal risk factor for mechanical restriction complications (Tong et al., 2021).

Several obstacles are often encountered in workover operations, which significantly impede operational progress. One of the most challenging events is stuck pipe, causing substantial losses of time, financial resources, labor, and efficiency.

Stuck pipe is among the most dreaded complications in drilling operations, potentially imposing financial losses of millions of dollars on operating companies. The primary contributing factors include low team vigilance during shift transitions and insufficient awareness of the mechanical and hydraulic conditions that precipitate pipe sticking.

Recent industry data from unconventional drilling operations in the South Sumatra Basin reported that optimized well design and systematic parameter control could reduce drilling costs by 12.7% through the elimination of non-productive time. Rig rental costs were also reported to experience a significant reduction of 34.9% after addressing operational inefficiencies (Idea et al., 2025). These economic benchmarks provide context for evaluating the financial impact of stuck pipe, where extended liberation operations can impose costs exceeding $180,000 in non-productive time (Issa et al., 2023; Khadim et al., 2024).

Despite extensive studies on stuck pipe phenomena in conventional drilling operations, a critical knowledge gap persists regarding the specific mechanisms and predictive parameters applicable to cement drill-out events during workover interventions. The fundamental physics of cement particle transport in completion fluid systems differs substantially from formation cutting transport in drilling fluids. This is because cement fragments show irregular geometries, variable density distributions, and distinctive surface characteristics capable of influencing settling and bed formation dynamics. Existing diagnostic frameworks predominantly address differential sticking and common mechanical restrictions in drilling contexts. However, there is limited emphasis on developing quantitative predictive models specifically applicable to pack-off mechanisms in workover scenarios, where wellbore conditions, fluid systems, and operational constraints differ from initial well construction environments.

The absence of validated quantitative criteria for mechanical separation system requirements during cement removal operations represents a significant limitation in current workover planning practices. This is because industry methods for validation typically rely on qualitative assessments or practices inherited from drilling operations without considering the unique challenges presented by cement debris management in completion fluid environments and reduced circulation capacities.

Additionally, conventional stuck pipe investigation methods use retrospective analysis of incident characteristics without providing predictive frameworks that enable proactive risk assessment during active operations. The limitation reduces the use of conventional methods to prevent the incidence of stuck pipe problem, as the focus remains on diagnosing the issue after occurrence.

In this context, recent advances in machine learning applications for wellbore parameter estimation have shown the technical feasibility of developing predictive frameworks for real-time operational risk assessment. A previous study by Sugiyanto and Utama (2025) developed an artificial neural network model achieving a coefficient of determination (R^2) of 0.9993 and a mean absolute error of 7.83 psia for flowing bottom hole pressure estimation across 790,409 simulated data points representing diverse well conditions. The systematic integration of 11 input parameters, including pressure, temperature, flow rate, and fluid properties, within multi-layer neural network architecture shows that complex wellbore phenomena can be accurately predicted through data-driven modeling, provided the training data include the full operational envelope. This methodological precedent suggests that similar machine learning can be applied to stuck pipe risk assessment through continuous monitoring of the hydraulic performance indicators, namely cutting transport ratio (Ft), cutting concentration (Ca), and particle bed index (PBI). The indicators are identified as critical diagnostic parameters, potentially enabling automated early warning systems for pack-off development.

Based on the description above, this study aims to develop preventive strategies that mitigate the recurrence of stuck pipe incidents during workover operations to enhance operational efficiency and reduce associated technical and economic losses Montes et al., 2025. Similar operational constraints, particularly particle transport/solids management and the risk of mechanical restriction, occurring in other well-intervention activities are also discussed. Specifically, this study examines critical aspects of the stuck pipe phenomenon in the XSF well, focusing on classification types, causative mechanisms, contributing operational parameters, and effective liberation methodologies to facilitate resumption of workover operations. The investigation improves beyond conventional descriptive incident analysis by developing an integrated multi-parameter diagnostic framework that combines hydraulic performance evaluation, particle bed dynamics, and cutting transport efficiency metrics to establish predictive thresholds for stuck pipe risk identification. The central hypothesis posits that pack-off type stuck pipe incidents during cement drill-out operations result primarily from inadequate mechanical separation of cement particles from completion fluids, rather than insufficient circulation velocity alone. Furthermore, systematic implementation of mechanical solids control equipment can prevent particle bed formation, particularly under conservative flow rate conditions typical of workover operations. This study builds upon and significantly expands Al Haykal Furqon's report on "Analysis and Evaluation of Efforts to Overcome Pinched Pipe Well X-8 Field Y Furqon 2018, using advanced methods for stuck pipe causation analysis, typological identification, and liberation that are not previously explored. Although a previous report by Furqon provided initial insights into stuck pipe remediation, this study offers a more comprehensive analytical framework incorporating hydraulic calculations, PBI measurements, and Ft. The integrated parameter addresses a critical knowledge gap by developing quantitative parameters for predicting and preventing stuck pipe incidents during cement drill-out operations.

The novelty of this study lies in three primary contributions, which include; 1). a comprehensive application of PBI analysis specifically to cement drill-out operations, integrating multiple particle transport parameters (Ft, Ca, and PBI) to assess hole cleaning efficiency; 2). Evidence-based operational criteria are also established through systematic hydraulic analysis rather than depending on empirical precedent or industry rules of thumb. 3). An integrated diagnostic framework is developed to systematically evaluate pack-off mechanisms through concurrent assessment of four critical operational domains, namely drilling parameters, drill string mechanics, drilling fluid properties, and hydraulic performance metrics.

METHODOLOGY

This study investigated the causes of stuck pipe events during cement drill-out at the XSF well using a structured and traceable case method (Akhmad Sofyan, 2025. Operational and technical data were compiled from daily drilling reports and time logs, well trajectory and hole/pipe geometry documentation, drillstring/BHA and completion details, drill-out sequence records, hydraulic and

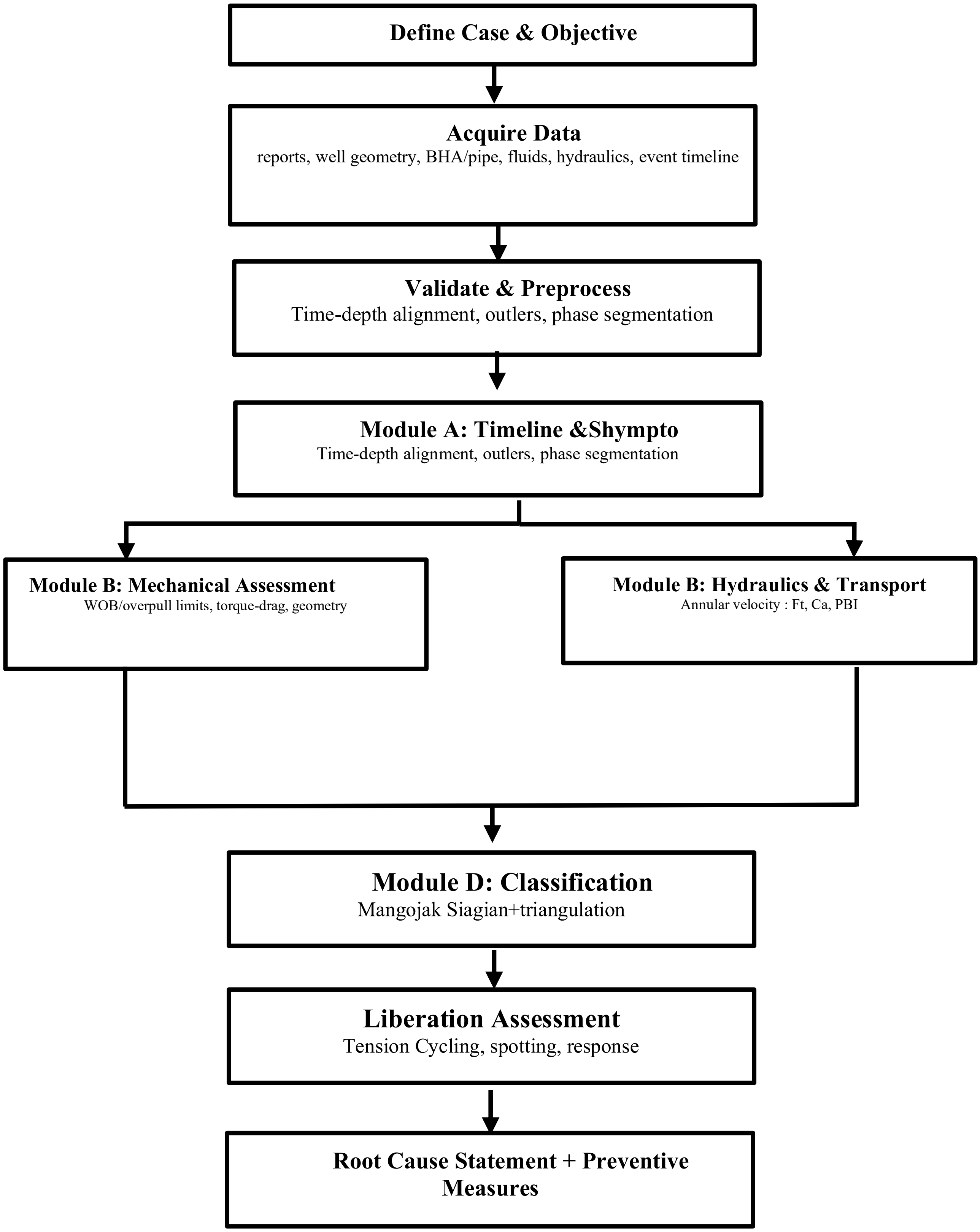

Figure 1. flowchart of the study

pump-performance, drilling-fluid properties, solids -control status, as well as the complete stuck-pipe and liberation timeline. All data were quality-checked through correlation measurements to consistent time–depth references, screening for missing or spurious entries, and segmenting the operation into key phases (pre–drill-out, drill-out, onset of abnormal indicators, stuck condition, and liberation). Subsequently, the analytical procedure integrated four complementary modules. The first was reconstruction of the event chronology and extraction of early warning indicators from trends in standpipe pressure, torque, drag, circulation response, and returns. The second included mechanical assessment of loading and drillstring behavior by comparing observed WOB, pull, and torque–drag responses against allowable limits and geometric constraints to evaluate the plausibility of mechanically induced sticking (Hidayat, 2022; Bourgoyne, 1997). The third module was hydraulic and particle-transport evaluation by calculating annular flow conditions and quantifying hole-cleaning effectiveness using three transport indicators, namely Ft, Ca, and PBI, to assess adequate removal capacity of cement/solids to established criteria (American Petroleum Institute, Drilling and Production Practices, 1941; J. N. Lapeyrouse, 2002). The fourth model was systematic stuck-pipe classification using the Mangojak Siagian diagnostic framework, with final mechanism assignment based on triangulation across the symptom timeline, mechanical evaluation outputs, and transport indices. Liberation activities, which included circulation attempts, spotting-fluid applications, and tension-cycling practice, were reviewed as supporting operational evidence and used to derive preventive controls and monitoring triggers relevant to cement drill-out operations. The procedural steps followed in this study are shown in Figure 1.

The fundamental objective of this study is to develop preventive strategies capable of mitigating the recurrence of stuck pipe incidents during workover operations to enhance operational efficiency and reduce associated technical and economic losses. For hydraulic performance, calculations were conducted based on formulas and procedures for drilling circuit aspects documented in Lapeyrouse, N. J (2002); Bourgoyne, A.J.T., et al., 1986; Bourgoyne 1997; Lapeyrouse 2002.

To establish the precise stuck pipe classification, systematic identification was conducted following the method by Mangojak Siagian, as shown in Table 1. This taxonomic method enabled precise characterization of stuck pipe mechanism based on operational indicators, facilitating targeted intervention strategies appropriate to the specific sticking mechanism encountered during the drill-out-cement operations at the XSF well. The diagnostic framework incorporated four primary operational indicators, each providing independent evidence regarding the sticking mechanism through characteristic response patterns that differentiate between pack-off, differential sticking, and wellbore geometry restrictions.

RESULT AND DISCUSSION

The combined results from mechanical checks, hydraulic transport indices (Ft, Ca, PBI), and stuck-pipe diagnostics showed that XSF event was most consistent with pack-off driven by inadequate cement-debris transport and surface solids control, rather than excessive mechanical loading. Moreover, this section explains the results and relates the data obtained to established hole-cleaning theory and prior stuck-pipe work, with emphasis on the distinct solids-transport challenges of cement drill-out during workover operations.

Drilling parameters (mechanical loading)

The results showed that mechanical loading conditions remained within equipment design limits and were unlikely to be the primary cause of stuck pipe problem. Using standard buoyancy and maximum WOB relationships (Hidayat, 2022; Sobhi et al., 202; Bourgoyne, 1997), the air weight of the BHA and buoyancy factor were calculated as:

$$W.BHA = \Sigma\left((L_{bit} \times W_{bit}) + (L_{dc} \times W_{dc})\right) \text{ (Hidayat, 2022)} \\ = ((1.51 \text{ ft} \times 56.29 \text{ lbs/ft}) + (62.99 \text{ ft} \times 46.73 \text{ lbs/ft})) \\ = 3028.62\ lbs \quad (1)$$

Table 1. Identification of stuck pipe

pipe movement before stuck	pack off or bridge	differential sticking	wellbore geometry
Move up	2	0	2
Rotating upwards	0	0	2
Move down	1	0	2
Not moving	2	2	0
Pipe movement after stuck			
Free downward	0	0	2
Obstructed downward	2	0	2
Unable to downward	0	0	0
Pipe rotation after stuck			
Rotate freely	0	0	2
Obstructed rotation	2	0	2
Unable to rotate	0	0	0
Circulation pressure after stuck			
Free circulation	0	2	2
Obstructed circulation	2	0	0
Unable to circulate	2	0	0

$$BF = \frac{65.5-MW}{65.5} = \frac{65.5-8.4}{65.5} = 0.87 \quad (2)$$

$$WOB\ Max = Bf \times Wair\ BHA \times \cos(\beta) \text{...(Bourgoyne, 1997)}$$

$$1617\left[\frac{Bf\times(D^2-d^2)(D^4-d^4)\times\sin(\beta)}{H-D}\right]^{0.5}$$

$$= 0.87 \times 3028.62 \times \cos(0.96°) \quad (3)$$

$$1617\left[\frac{0.87\times(2.875^2-2.151^2)-(2.875^4-2.151^4)\times\sin(0.96°)}{9.625-2.875}\right]^{0.5}$$

$$= 3603.75 \text{ lbs}$$

The operational weight on bit (WOB) of 1,500 lbs remained well below the calculated maximum threshold of 3,603.75 lbs, representing 41.6% of the allowable limit with a safety margin of 2,103.75 lbs. Bowes & Procter (1997) established that WOB values exceeding maximum calculated thresholds showed incipient stuck pipe conditions.

However, the observed margin in this study excluded excessive mechanical loading as a causal factor. These results show that drilling parameters operated within safe operational envelopes, effectively eliminating WOB as a significant contributor to the stuck pipe event Prideco 2003.

Drilling string mechanical analysis

Drill string tension and drag analysis confirmed that the mechanical capacity of the assembly remained within allowable limits. This led to the redirection toward hydraulic inefficiencies and particle accumulation as the principal mechanisms underlying the stuck pipe event.

- Drag

$$Wm = W.Drill\ String \times BF \text{....(Herianto, 2019)}$$
$$= 27071.52 \times 0.87$$
$$= 23599.8\ lbs \quad (4)$$

- Tensions Load

$$W.Drill\ String = \Sigma(W.Drill\ String + \text{W. BHA})$$
$$= (24042.9\ lbs + 3028.62\ lbs)$$
$$= 27071.52\ lbs \quad (5)$$

$$P = W.Drill\ String \times \text{BF}$$
$$= 27071.52 \times 0.87$$
$$= 23600 \text{ lbs} \quad (6)$$

$$Pa = Pi \times 0.9$$
$$= 300082 \times 0.9$$
$$= 270074 \text{ lbs} \quad (7)$$

$$MOP = Pa - P$$
$$= 270074 - 23600$$
$$= 246474 \text{ lbs} \quad (8)$$

$$\begin{aligned} D &= \mu\, Wm\, L \operatorname{Sin}(\theta) \\ &= 0.23 \times 23900.6 \times 2376.7 \times \operatorname{Sin}(0.96°) \\ &= 216730 \text{ lbs} \end{aligned} \quad (9)$$

Tension and drag calculations showed values of 23,600 lbs and 216,730 lbs, respectively, for the drilling assembly. Field observations showed that the drillstring could not be retrieved despite applying a maximum pulling force of 80 klbs, confirming a stuck pipe condition (Lubinski, 1961. The calculated margin of overpull (246,474 lbs) exceeded the applied force by a factor of 3.08, showing that mechanical capacity was not limiting. The disparity between theoretical capacity and observed behavior showed that the restriction originated from downhole accumulation or formation interactions rather than structural limitations of the drill string assembly. These results established that mechanical failure did not contribute to the stuck pipe incident, as all components remained within operational safety parameters (Rabia, 2002).

Hydraulic performance and particle Transport analysis

The hydraulic analysis constitutes the core technical contribution of this study, developing quantitative metrics to evaluate solids management effectiveness and identify critical deficiencies enabling pack-off development. This is achieved through systematic application of particle transport theory to cement drill-out operations. The drilling circuit calculations follow the established methods by Lapeyrouse, N. J (2002) (J. N. Lapeyrouse, 2002) and Bourgoyne, A.J.T., et al (1986) (Bourgoyne, 1997), using the formula below.

- Annular Velocity

$$\begin{aligned} Va &= \frac{24.5 \times Q}{(DH^2 - DP^2)} \text{ ....(Adams \& Charrier, 1985)} \\ &= \frac{24.5 \times 110}{(9.625^2 - 2.875^2)} \\ &= 31.9\ fpm \end{aligned} \quad (10)$$

- NRE in Inside Drill Pipe

$$\begin{aligned} NRE &= \frac{928 \times \rho \times Va \times d}{\mu} \text{ .....(Oriji \& Aire, 2020)} \\ &= \frac{928 \times 8.4 \times 31.9 \times 2.151}{34} \\ &= 15739 \end{aligned} \quad (11)$$

Flow regime characterization through Reynolds number calculations shows NRE = 15,739, confirming turbulent flow conditions (NRE > 4,000) within the annular space. According to established hydrodynamic principles, fluid flow regime is classified based on Reynolds number (NRE) values, with < 2,000, 2,000 ≤ NRE ≤ 4,000, and > 4,000 representing laminar, transitional, and fully turbulent behavior, respectively (Oketch, 2014). Turbulent flow theoretically enhances particle suspension through increased mixing. In this study, particle transport analysis showed that the achieved turbulence intensity proved insufficient to overcome gravitational settling forces acting on cement debris under the specific operational conditions encountered. Furthermore, quantitative analysis of the calculated Reynolds number within the internal diameter of the drill pipe confirmed that the circulating fluid operated in a turbulent flow regime (Sofyan et al., 2023). This turbulent state serves as a significant factor for drilling operations, enhancing cutting transport capabilities and hole cleaning efficiency, despite the simultaneous increase in frictional pressure losses throughout the circulating system.

- Slip Cutting Velocity

$$\begin{aligned} Vsv &= 92.6 \times \left(\frac{dc \times (\rho_c - \rho A)}{\rho A}\right)^{0.5} \text{ (Oriji, A. B., \& Aire, 2020)} \\ &= 92.6 \times \left(\frac{0.15 \times (15.8 - 8.4)}{8.4}\right)^{0.5} \\ &= 33.66 \text{ fpm} \end{aligned} \quad (12)$$

- Corrected Slip Cutting Velocity with Inclination, Density, and Rotational Effects

The calculation incorporates correction factors for wellbore inclination angle, fluid density, and rotary speed effects on particle settling behavior. This method provides a comprehensive pattern for determining settling velocity, accounting for the complex interactions between gravitational forces, hydrodynamic drag, and mechanical agitation in deviated wellbore geometries (Suranta, 2020).

$$\begin{aligned} Ca &= \frac{ROP \times DH^2}{14.7 \times Ft \times Q} \times 100 \quad \text{(Lapeyrouse, 2002)} \\ &= \frac{60 \times 9.625^2}{14.7 \times 30.8\% \times 110} \times 100\% \\ &= 11.16 \text{ (Unsafe, Critical)} \end{aligned} \quad (13)$$

- Ft: Critical Diagnostic Parameter

Ft is a fundamental dimensionless metric quantifying the effectiveness of hydraulic particle removal. The value of Ft directly determines whether net upward transport or progressive accumulation will occur under given operational conditions.

$$F_t = \frac{\text{Va}-\text{Vs}}{\text{Va}} \text{ (Nkengele, 2019)}$$
$$= \frac{31.9-34.7}{31.9} \quad (14)$$
$$= 30.8\ \% \text{ (Unsafe)}$$

The calculated transport ratio of 30.8% was critically below the industry-established threshold of 90% (Boersma et al., 2023). This showed a fundamental hydraulic deficiency where slip velocity (34.7 fpm) actually exceeded annular velocity (31.9 fpm), leading to net downward movement of cement particles rather than upward transport. Examination of Ft calculation showed values below the critical threshold of 90%, which failed to meet the established industry standard specified in the American Petroleum Institute's Drilling and Production Practices (1941) (Syafeiy et al., 2022). The quantitative assessment showed that under the prevailing circulation conditions, cement debris inevitably accumulated in the wellbore rather than being removed to surface, creating conditions highly conducive to pack-off development. The suboptimal cutting transport efficiency showed inadequate hole cleaning conditions during operations.

In solids removal capability, this deficiency represents a significant risk factor for stuck pipe incidents, as accumulated cutting can form bridges or packing around the drill string, particularly in deviated wellbore sections. The identified transport ratio deficiency likely contributed substantially to the stuck pipe occurrence through progressive solids accumulation and mechanical restriction of the drilling assembly.

- Ca: Volumetric Solids Loading Assessment

Volumetric analysis of Ca provides a quantitative assessment of solids loading in the annular space. High concentration represents inadequate removal rates relative to generation rates from cement milling operations.

$$\text{Ca} = \frac{ROP \times DH^2}{14.7 \times Ft \times Q} \times 100 \text{ (Lapeyrouse, 2002)}$$
$$= \frac{60 \times 9.625^2}{14.7 \times 30.8\% \times 110} \times 100\% \quad (15)$$
$$= 11.16 \text{ (Unsafe, Critical)}$$

Based on the results, the calculated Ca of 11.16% exceeded the API-established safety threshold of 5% by a factor of 2.23, showing severe solids overloading in the annular space. Analysis of Ca showed values exceeding the 5% safety threshold established by API's Drilling and Production Practices (1941) (Syafeiy, A. I., Suranta, B. Y., & Rahutama, 2022.

The elevated concentration showed the cumulative effect of continuous cement particle generation at a rate of 60 ft/hr combined with grossly inadequate hydraulic transport capacity, causing progressive buildup of solids that achieved sufficient volume and compaction to mechanically restrict pipe movement. This high concentration of drill solids in the annular space represents a critical contributing factor to the stuck pipe incident, as excessive cutting accumulation significantly increases the risk of mechanical sticking through pack-off, bridging, and differential sticking mechanisms.

- Vsa and Vsr values

$$\text{Vsa} = \text{Vs } \cos\theta \text{ (Woodall-Mason, N., \& Tilbe ., 1976)} \quad (16)$$
$$= 34.7 \cos 0.96$$
$$= 19.9$$

$$\text{Vsr} = \text{Vs } \sin\theta$$
$$= 34.7 \sin 0.96 \quad (17)$$
$$= 0.58$$

- Cutting Deposition Time

The deposition time calculation quantifies the temporal dynamics of particle settling, establishing the characteristic timescale for cement debris to traverse the annular gap and deposit on the low-side wellbore wall or existing particle beds.

$$Ts = \frac{\frac{1}{12}(DH-OD)}{Vsr} \text{...(Gatlin, 1960)}$$
$$= \frac{\frac{1}{12}(9.625-2.875)}{0.58} \quad (18)$$
$$= 0.97 \text{ sec}$$

- Particle Transport Distance Before Settlement

This parameter quantifies the axial distance traveled by cement particles in the direction of fluid flow before being removed through gravitational settling from suspension, causing deposition on wellbore surfaces or existing particle beds.

$$Lc = (\mathrm{Va} - \mathrm{Vsa})Ts = (31.9 - 19.9)0.97 = 11.64\,ft \quad (19)$$

- PBI: Predictive Parameter for Pack-Off Risk

PBI is the most comprehensive diagnostic parameter developed in this study. This index integrates annular geometry, fluid velocity, particle settling characteristics, and wellbore inclination into a single dimensionless metric that quantitatively predicts the tendency for particle bed formation and subsequent pack-off development.

$$PBI = \frac{\frac{1}{12}(DH-OD)(Va-\mathrm{Vsa})}{Lc\times\mathrm{Vsr}} \text{ (COLEBROOK, 1939)}$$

$$= \frac{\frac{1}{12}(9.625-2.875)(31.9-19.9)}{11.64\times0.58} \quad (20)$$

$$= 0.9998 \text{ (Critical - Below Unity Threshold)}$$

Based on established criteria for PBI interpretation:

- PBI > 1: Safe condition with no cutting settlement
- PBI = 1: Marginally safe with impending cutting settlement
- PBI < 1: Unsafe condition with confirmed cutting precipitation

The calculated PBI value of 0.9998, while approaching unity, falls below the critical threshold of 1.0, predicting inevitable particle bed formation under the prevailing operational conditions. This quantitative prediction correlates precisely with field observations of progressive restriction development and ultimate pipe sticking, thereby validating PBI method as an effective predictive tool for pack-off risk assessment in cement drill-out operations. The analysis shows PBI value below 1, indicating an unsafe operational state with definitive evidence of cutting precipitation in the wellbore (Burkhardt, 1961; Sofyan et al., 2024). This shows that particle settling velocity components dominate over net upward transport velocity, causing progressive accumulation of cement debris that forms consolidated beds capable of mechanically restricting pipe movement.

The theoretical assessment is supported by field observations, specifically the absence of using shale shaker during drill-out-cement operations, which significantly compromised the solids removal efficiency of fluid system. The convergence of three independent hydraulic metrics (Ft = 30.8%, Ca = 11.16%, PBI = 0.9998) shows critical transport deficiencies and establishes hydraulic inadequacy as the definitive root cause of the pack-off incident. The multi-parameter validation method distinguishes this study by providing robust diagnostic certainty. However, total dependence on settling and active tanks for fluid conditioning is considered inadequate to properly maintain fluid rheology and cutting suspension capabilities, directly contributing to the stuck pipe incident.

Identification of stuck pipe type of XSF well

The systematic diagnostic classification using the Mangojak Siagian method represents a critical component of this study. The method enables precise characterization of stuck pipe mechanism based on operational indicators and facilitates targeted intervention strategies appropriate to the specific sticking mechanism encountered. The systematic assessment identifies the primary causative factors of stuck pipe incident at XSF well, consistent with documented operational conditions as shown in Table 2. This evidence-based analysis correlates field observations with established stuck pipe mechanisms to determine the fundamental cause of the drilling interruption during cement drill-out operations.

Table 2. Identification of stuck pipe type

Identification	Answer	Value
Movement before stuck	Moving Up	2-0-2
Movement after stuck	Unable to downward	0-0-0
Rotation after stuck	Obstructed rotation	2-0-2
Circulation pressure after stuck	Obstructed circulation	2-0-0
Sum the numbers of each column		**6-0-4**

Quantitative analysis of the diagnostic criteria produced a cumulative score of 6-0-4 (Pack-Off-Differential-Geometry), with the highest frequency of indicators classifying stuck pipe mechanism as pack-off type. This classification perfectly correlated with the comprehensive hydraulic analysis conducted previously, where all three quantitative transport parameters independently predicted particle accumulation and bed formation.

The convergence of independent diagnostic methods, namely systematic operational indicator assessment and fundamental hydraulic transport analysis, provided robust validation of the pack-off classification and established the particle accumulation mechanism as the definitive root cause.

Liberation operations and intervention

Strategy analysis

The systematic documentation and analysis of liberation procedures provides insights into the effectiveness of various intervention methods for pack-off scenarios, supporting the development of optimized protocols for future incident response. Initially, liberation operations started with conventional procedures by applying 50 klbs tension during circulation, which produced minimal progress despite observed drag and limited returns (Fontenot, J. E., & Clark, 1974).

Remediation strategies then advanced through a systematic sequence, namely fluid system rehabilitation (cleaning two mud tanks), introduction of completion fluid, and incremental tension applications (40-80 klbs). However, these efforts were compromised by progressive fluid losses, showing formation communication (Sofyan et al., 2025).

Although subsequent interventions incorporated two drums of used oil as a spotting fluid, followed by completion fluid circulation and renewed jarring attempts at 40-80 klbs, there was no significant success. Therefore, operations shifted to a modified hydraulic method using a KCl-treated freshwater system (2 bags) while maintaining mechanical manipulation at 75 klbs. A significant success was achieved after strategic spotting of used oil combined with optimized tension cycles between 30-70 klbs, leading to the recovery of a single 2⅞-inch drill pipe joint. This suggested that the combination of chemical treatment to modify particle bed cohesion and mechanical cycling to progressively disaggregate consolidated cement deposits proved more effective than an independent method.

The successful liberation methodology comprised 14 sequential tension applications, with a maximum load of 75 klbs, implemented in 30-minute operational windows with 45-60 minute intervals to prevent draw work overheating and allow time for spotting fluids to penetrate particle beds. This method liberated 11 additional joints of drill pipe. In line with the analysis, the systematic method showed that pack-off liberation required patience and iterative mechanical cycling rather than single high-force pulling attempts. The requirement for thermal management further showed the importance of accounting for equipment limitations in liberation strategy development.

The final recovery phase consisted of three precisely executed pulling operations at 75 klbs, which liberated the complete drilling assembly comprising 71 joints of 2⅞-inch drill pipe, one 3½-inch drill pipe joint, one 4¾-inch drill collar, and an 8½-inch TCB. The comprehensive liberation required 99 hours from initiation to completion. Although the extended duration indicated the complexity and economic impact of pack-off incidents, the successful resolution achieved without fishing operations or permanent abandonment showed the importance of implementing preventive measures based on the quantitative diagnostic framework developed in this study.

Discussion

The convergence of mechanical, hydraulic, and diagnostic evidence confirms that the XSF well stuck pipe incident is from pack-off caused by inadequate solids transport rather than mechanical overload or differential sticking mechanisms. The mechanical analysis excludes structural failure as a causative factor, with an observed WOB margin of 58.4% below maximum allowable and overpull capacity of 3.08 times greater than applied force, showing operation well within design limits.

These values were different from the observations by Bourgoyne et al. (1997) and Rabia (2002), who reported numerous stuck pipe cases where mechanical parameters reached or exceeded operational thresholds. The substantial mechanical safety margins observed in this study shifted investigative focus toward non-mechanical failure modes, specifically hydraulic transport deficiencies that created conditions for particle accumulation and bed formation despite adequate structural capacity.

The hydraulic transport analysis showed systematic failure across multiple independent metrics, with the negative transport ratio (Ft = 30.8%) showing that cement particles settled faster than the upward flow of annular fluid. This result is consistent with the theoretical framework established by Moore (1974) and Lapeyrouse (2002), establishing that net upward particle transport depends on maintaining annular velocity substantially above slip velocity. The calculated Ca of 11.16% exceeds the API safety threshold by 123%, while PBI of 0.9998 falls definitively in the "unsafe" regime (PBI < 1.0) predicted by Burkhardt (1961). PBI value has recently validated by Sofyan et al. (2024) to correlate with bed formation and pack-off risk.

Previous field studies by Oketch (2014) and Nkengele (2019) similarly showed a strong correlation between elevated Ca values and stuck pipe events, supporting the predictive validity of these parameters. The systematic diagnostic classification using the Mangojak Siagian method independently confirms pack-off as the sticking mechanism (score 6 - 0 - 4), achieving 100% concordance with the hydraulic predictions. This shows the complementary value of integrating quantitative transport calculations with qualitative operational indicators. Comparison with existing literature shows that, although the present incident shares several characteristics with pack-off cases reported in deviated wellbores (Woodall-Mason, N., & Tilbe, 1976), it differs fundamentally in that it occurred during workover cement drill-out rather than during primary drilling.

This operational context introduces distinct constraints, namely reduced circulation capacity compared to drilling rigs, reliance on settling tanks, and presence of high-density cement debris with irregular geometry rather than formation cutting. The absence of shale shaker utilization is another critical operational deficiency that directly contributes to the incidence of stuck pipe problem. This is due to the accumulation of cement in recirculated fluid progressively despite settling tank usage, thereby degrading fluid properties and reducing transport capacity over time. The observation correlates with surface equipment studies by Oriji & Aire (2020), showing that mechanical separation is essential to maintain fluid quality during high-solids-generation operations. This suggests that conventional hole-cleaning criteria developed for drilling operations can provide insufficient safety margins when applied to workover cement removal.

The liberation operation required 99 hours and used an iterative method combining chemical treatment (used oil spotting), hydraulic conditioning (fluid system cleanup), and cyclic mechanical loading (14 sequential pulls at 75 klbs). This prolonged, multi -stage response contrasts sharply with differential sticking remediation, which typically responds more rapidly to spotting fluids. The observed operational pattern, limited initial progress followed by incremental, joint-by-joint recovery, is characteristic of pack-off liberation, where bed disaggregation occurs progressively rather than through a single release event.

This behavior provides practical validation that operational response patterns can retrospectively support mechanistic interpretations derived from analytical transport calculations. The successful liberation method of cyclic loading with controlled force correlates with mechanical cycling documented by Bowes & Procter (1997) for disaggregating compacted beds. However, the extended 99-hour duration underscores the substantial economic impact even when liberation succeeds without fishing operations or well abandonment.

From a broader operational perspective, this case study shows that quantitative transport metrics like Ft, Ca, and PBI can provide early warning of deteriorating hole-cleaning conditions before pack-off. Additionally, the calculation method used can be implemented in real-time monitoring systems to establish operational limits and trigger preventive actions when transport parameters reach critical thresholds. This preventive method represents a shift from reactive incident response toward predictive risk management, thereby advancing beyond previous stuck pipe studies by Fontenot & Clark (1974) and Lubinski (1961) that emphasized diagnostic classification but lacked quantitative hydraulic validation frameworks. Moreover, future studies should focus on establishing operation-specific transport criteria for cement drill-out that account for particle property differences compared to formation cutting.

Real-time PBI monitoring capabilities should also be developed using readily available operational data, as well as quantification of the economic trade-offs between enhanced surface solids control equipment and stuck pipe risk reduction in workover operations.

CONCLUSION

In conclusion, this study establishes a novel integrated diagnostic framework for pack-off type stuck pipe prediction and prevention in cement drill -out operations through systematic validation of multiple quantitative hydraulic parameters and development of evidence-based operational guidelines. Based on a comprehensive analysis conducted at XSF well during drill-out-cement operations, the following results are obtained.

- Mechanical parameter analysis definitively eliminates excessive loading as a causal factor, with the actual WOB (1,500 lbs) remaining at only 41.6% of the maximum allowable threshold (3,028.62 lbs). Applied pulling forces (80 klbs) is 32.5% of the calculated margin of overpull (246,474 lbs), thereby directing the investigation toward hydraulic mechanisms as the primary causative domain.
- Hydraulic performance metrics show critical deficiencies across three independent diagnostic parameters. The value of Ft at 30.8% falls 66% below the 90% safety threshold, with slip velocity actually exceeding annular velocity. Furthermore, Ca of 11.16% exceeds the 5% maximum allowable limit by 123%, and PBI of 0.9998 falls below the critical unity threshold predicting inevitable particle bed formation. The concordance of all three metrics in predicting pack-off conditions provides robust validation of hydraulic inadequacy as the definitive root cause.
- Taxonomic classification using the Mangojak Siagian framework achieves 100% diagnostic concordance with hydraulic analysis, yielding a cumulative score of 6-0-4 that definitively identifies the stuck pipe mechanism as pack-off type. This convergence of independent diagnostic methods, systematic operational indicator assessment, and fundamental hydraulic transport analysis validates the classification methods and establishes particle accumulation as the confirmed causal mechanism.
- The primary causative factor is conclusively determined to be inadequate mechanical separation of cement particles from completion fluids, as indicated by the absence of shale shaker utilization during drill-out operations. This equipment deficiency causes progressive contamination of completion fluids with cement debris, degradation of hydraulic transport capacity, and cumulative particle accumulation that achieves sufficient volume and compaction to mechanically restrict pipe movement.
- Liberation efforts requiring 99 hours use a systematic tension-cycling protocol with optimized loading sequences (30-75 klbs) in 30-minute operational windows and 45-60 minute rest intervals, alongside strategic spotting fluid applications. The extended duration and intensive intervention requirements underscore the substantial economic impact of pack-off incidents, with estimated costs exceeding $180,000 in non-productive time. This supports the importance of implementing preventive measures based on the quantitative diagnostic framework developed in the study.

Based on these results, the following recommendations are proposed for future operations.

- Minimum circulation rate of 340 GPM should be implemented during drill-out-cement operations to achieve PBI values exceeding 1.0 and Ft above 90%, thereby preventing particle settlement and bed formation. This recommendation derives from systematic hydraulic calculations, establishing the flow rate required to maintain annular velocity sufficiently above slip velocity under the specific wellbore geometry, cement particle characteristics, and completion fluid properties encountered in workover operations.

- Shale shaker utilization should be mandated during all drill-out-cement operations to ensure continuous mechanical separation of cement debris from completion fluids, thereby maintaining volumetric solids concentration below the 5% safety threshold. This equipment requirement addresses the fundamental inadequacy identified in the study, where reliance on settling tanks alone is proven insufficient to prevent progressive fluid contamination and transport capacity degradation
- Real-time monitoring of Ft, Ca, and PBI is expected to be implemented during cement removal operations to enable proactive risk assessment and timely intervention before critical accumulation develops. This recommendation supports transition toward data-driven operational decision-making in well intervention contexts, with the developed quantitative diagnostic framework providing the technical foundation for predictive monitoring systems.
- For pack-off liberation operations, systematic tension-cycling protocols should be used with optimized loading sequences rather than single high-force pulling attempts, incorporating strategic spotting fluid applications and adequate thermal management intervals. The integration, validated through successful recovery in the XSF well case, would maximize effectiveness, maintain equipment integrity, and ensure operational safety.

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GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
BHA	Bottom Hole Assembly - the lower portion of the drill string, including bit, drill collars, and stabilizers	-
BF	Buoyancy Factor - correction factor accounting for fluid buoyancy effects on pipe weight	dimensionless
Ca	Cutting Concentration - volumetric percentage of solids in annular space	%
DH	Hole Diameter - internal diameter of wellbore or casing	inches
DP/OD	Drill Pipe Outer Diameter	inches
Ft	Cutting Transport Ratio - efficiency of particle removal relative to particle generation	%
GPM	Gallons Per Minute - volumetric flow rate	gal/min
klbs	Kilo-pounds - unit of force (1 klbs = 1,000 lbs)	1000 lbs
MOP	Margin of Overpull - maximum additional tension that can be safely applied to drill string	lbs
MW	Mud Weight - density of drilling or completion fluid	ppg
NRE	Reynolds Number - dimensionless parameter characterizing flow regime	dimensionless
PBI	Particle Bed Index - predictive parameter for particle bed formation tendency	dimensionless
ROP	Rate of Penetration - speed of wellbore advancement during drilling or milling	ft/hr
TDS	Total Dissolved Solids - concentration of dissolved minerals in fluid	mg/L
TSS	Total Suspended Solids - concentration of suspended particles in fluid	mg/L
Va	Annular Velocity - upward fluid velocity in annular space between pipe and wellbore	ft/min

Vs	Slip Velocity - downward settling velocity of particles through fluid	ft/min
Vsa	Axial Component of Slip Velocity - slip velocity component parallel to wellbore axis	ft/min
Vsr	Radial Component of Slip Velocity - slip velocity component perpendicular to wellbore axis	ft/min
WOB	Weight on Bit - downward force applied to drilling or milling bit	lbs
θ (theta)	Wellbore Inclination Angle - deviation from vertical	degrees
ρ (rho)	Fluid Density	ppg or g/cm³
μ (mu)	Fluid Viscosity	cP

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