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# A Comprehensive Review of the Pipe Sticking Mechanism in Oil Well Drilling Operations

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## ABSTRACT

As stuck pipe holds on to be a prime contributor to non-productive time (NPT) in drilling industry operations, efforts to restrict its incidence cannot be over-emphasized. Historically, stuck-pipe events have been shown to cost the industry several hundred million dollars annually and over 25% of non-productive time. British Petroleum Company's stuck pipe costs exceed $30 million annually. Industry-stuck pipe costs are estimated to be above $250 million annually. Major causes of this issue involve wellbore instability, differential sticking forces, improper hole cleaning, and the forming of drill-cutting beds, especially in high-angle wells. One strategy for avoiding stuck pipe issues is to predict by using the available drilling data, which can be utilized to adjust drilling parameters. Preventing stuck pipes requires close monitoring of early warning signs, such as increases in torque and drag, excessive cuttings loading, tight spots while tripping, and loss of circulation while drilling. A machine learning (ML) approach was employed to identify warning signals and anticipate stuck pipe events due to its ability to handle complex parameter relationships. This article proposes an extensive comprehensive review of challenges associated with pipe-sticking issues to detect warning signs and early indicators of a stuck pipe during drilling to prevent it and provide operational recommendations for avoiding or freeing stuck pipes. Finally, this research paper analyzes and consolidates the idea of the importance of Artificial Intelligence (AI) methods for predicting the condition of stuck pipes during well drilling.

**Keywords:** Stuck pipe, Machine learning, Differential sticking, Non-Productive Time (NPT).

## 1. INTRODUCTION

A stuck pipe is a complicated and common accident in the well-site drilling process. Dealing with this accident is very complex and tedious, with high risk. According to this, there are various types of stuck pipes **(Zhu et al., 2019)**. The root causes of stuck pipe incidents are wellbore instability, improper hole cleaning, poor well trajectory, improper drilling fluid,

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hole assembly design, differential sticking forces, and human errors when there isn't good pogroms execution. Stuck pipe is a common problem in the petroleum industry, accounting for hundreds of millions of dollars in losses globally annually and causing several complications while drilling. As a result, efforts have been made to identify the causes of stuck pipes, potentially reducing the chances of the issue's occurrence **(Shoraka et al., 2011)**. Historically, BP's (BP is an abbreviation for British Petroleum, a multinational oil and gas company) stuck pipe has totalled more than $30 million annually. At the same time, estimates suggest that the industry's stuck pipe costs are over $250 million annually **(Bradley et al., 1991)**. It is possible to use data from logs used during drilling to diagnose possible pipe sticking **(Assi, 2023)**. A stuck pipe event is one of the most severe incidents that can occur during drilling operations; it results in nonproductive time and can even lead to well abandonment in the worst-case scenario. **(Muqeem et al., 2012)** stated stuck pipe incidents accounted for 25% of the nonproductive time, equivalent to at least two rig years. **(Abd Alhaleem et al., 2015)** demonstrated drilling directional wells increases the risk of pipe sticking, especially in the directed part. The issues related to this phenomenon can vary in intensity from minor sensitivity, leading to slight cost increases, to considerable problems, resulting in significant adverse impacts like the loss of the drill string or complete well loss. It's more probable that the pipe will get stuck during the drilling process, primarily through minimum pressure and depleted reservoir zones. Regular pipe sticking is a significant issue when drilling extended-reach wells in the eastern South China Sea **(Zhao et al., 2022)**. When it comes to drilling, diamond drills outperform conical bits and are less likely to get stuck **(Assi, 2017)**. The distribution of events in each category changes depending on the type of well and the geographical location. An oil company estimated that 29% of the investment associated with the stuck pipe was related to differential difficulties, while 70% was caused by mechanical sticking in its North Sea wells. On the other hand, differential sticking accounted for 61% of the overall cost of inactivity occurrences in the Gulf of Mexico **(Zhu et al., 2019)**. The use of polymer clay can reduce the possibility of pipe sticking due to its good lubrication, low solid material content, consistent texture, and non-thick cake **(Assi, 2018)**. The key to economizing and success is avoiding the risks that lead to stuck pipe events. If these risks are recognized in advance, procedures can be set up to minimize the possibility of stuck pipes and, therefore, to decrease the costs associated with freeing stuck pipe. Many researchers recently applied machine learning techniques (artificial intelligence methods) to detect this issue, as shown in **Table 1.** The artificial neural networks (ANN) technique is particularly good at handling data with quality issues such as those often faced in drilling operations. The main objective of this paper is to provide several ideas for better predicting the stuck pipe conditions to reduce stuck pipe costs and offer a comprehensive review of the challenges associated with pipe sticking in drilling processes. Identify trends that may include helpful guidelines for preventing or resolving stuck pipe events. This article comprehensively reviews the pipe-sticking problems, emphasizing the mechanisms that may arise during drilling operations. Additionally, diagnosis approaches and different treatment methods are discussed to mitigate the complications caused by the stuck pipe. It aims to help individuals in the petroleum industry understand and address the challenges related to stuck pipes.

**Table 1.** Previous studies related to stuck pipe incidents.

| Researchers | Findings, study, technique, method or model |
|---|---|
| **(Hempkins et al., 1987)** | The analytic technique was developed to estimate the chance the drill pipe will become stuck in a well. Discriminant analysis distinguished between mechanically stuck, differentially stuck, and non-stuck groups. Twenty standard drilling parameters were evaluated to determine the probability of a stuck pipe. The final result yielded 87% correct classification of wells. |
| **(Courteille and Zurdo, 1985)** | A new theoretical and experimental study of the forces involved along the pipe/cake/formation triple bond was presented when differential pressure sticking was established. Various mud kinds were examined, and novel strategies for preventing differential pressure sticking were proposed. They verified that the cake's thick consistency causes it to lose permeability near the cake/pipe border. Presenting established solids into the mud can be beneficial in situations when there is the opportunity for differential sticking. |
| **(Bradley et al., 1991)** | They have analyzed practices to drastically decrease expenses related to stuck pipe incidents in wells in the North Sea and the Gulf of Mexico. The task force identified numerous methods to reduce stranded pipe costs quickly. The handover process during a shift change was recognized as the cause of 36% of all stuck pipe events. |
| **(Howard and Glover, 1994)** | Multivariate Discriminant Analysis (MDA) was used to create predictive models for stuck pipe situations in wells constructed and drilled in the Gulf of Mexico and North Sea zones. The stuck pipe prediction plot provides a promising way to monitor wells during drilling operations. Multivariate discriminant analysis is a highly effective method for developing a predictive model that can classify drilled wells into three categories: mechanically stuck, not stuck, and differentially stuck. |
| **(Siruvuri et al., 2006)** | The neural network method is used to predict and understand the reasons behind incidents involving stuck pipes. Extensive simulations and case studies were conducted in the Gulf of Mexico. The predictive model's accuracy depends on the database size and selected variables. Neural networks can help understand the causes of differentially stuck pipe. |
| **(Shadizadeh et al., 2010)** | The Artificial Neural Network (ANN) technique was applied to find a stuck pipe in one Iranian oil field, which showed the importance of data preprocessing and selecting relevant input parameters related to the stuck pipe. This study established the newly developed dimensionless parameter known as the Geometric Factor (GF) may offer more significant advantages. Over 90% accuracy was achieved in predicting stuck pipe incidents in the oilfield under investigation. |
| **(Muqeem et al., 2012)** | Summarized the efforts of a task force formed by Saudi Aramco to minimize stuck pipe incidents related to NPT and provided the best practice documents generated to avoid stuck pipe incidents. It also includes recommendations for freeing stuck pipes with various spotting fluids and a decision tree to reduce stuck pipe-related NPT. They showed that stuck pipe incidents accounted for 25% of the nonproductive time, equivalent to at least two rig years. |
| **(Amin and Alhaleem, 2018)** | The stuck pipe events were investigated using the graphical analytic software Easy View. The research focused on Khabaz Field well-34. They also offered recommendations for mud formulation and Optimizing casing set design by addressing problems individually to mitigate risks and challenges. |

| | |
|---|---|
| **(Alshaikh et al., 2019)** | They presented models utilizing machine learning methods to identify crucial drilling parameters and detect stuck pipe abnormalities. This model can effectively see the signs by experts and help. The model improved the monitoring and interpretation of drilling data. |
| **(Elmousalami and Elaskary, 2020)** | This study compared machine learning (ML) algorithms for drilling piping stuck prediction. The drilling data from the Gulf of Suez wells is used as a real dataset to assess the efficacy of machine learning models. Twelve machine learning techniques, including artificial neural networks, logistic regression, scalable boosting trees, and random forests, are utilized for extracting stuck pipe. The results showed that the most effective algorithm was the highly randomized trees (extra trees) with 100% classification accuracy based on the testing dataset. |
| **(Malki et al., 2023)** | Demonstrated the physical model-based analysis using hole cleaning and hydraulics transient models, torque and drag soft string model, and machine learning algorithms for the early detection of stuck pipe, representing significant NPT sources in drilling operations. |

## 2. PIPE STICKING: CONCEPT AND MECHANISMS

### 2.1 Definition and Explanation of Stuck Pipe

A "stuck pipe" is a resistance phenomenon drilling mud to flow inside the annular space, making it impossible to move the pipe up or down. When a pipe is completely stuck, neither flow nor movement is available **(Siruvuri et al., 2006)**. Shell's Petroleum Development Company in Nigeria, the dominant Niger Delta operator, a stuck pipe generated 80% of the drilling time lost **(Magaji et al., 2002)**. The best solution to a stuck pipe is to recognize the environments in which it is likely to occur and avoid them **(Weakley, 2000).** Analysis of previous stuck pipe occurrences revealed that enhancing the detection and early warning systems for potential stuck pipe issues will enable the rig team to prevent numerous significant incidents.

### 2.2 Stuck Pipe Generation Mechanisms

The drill string becomes stuck during drilling activities and cannot be raised, lowered, or rotated. This condition can be caused by many factors, including sloughing of the hole wall, settling of large particles carried by the mud, buildup of mud filter cake during a long absence of circulation, and, finally, sticking by the pressure of the mud column conducting the pipe against the filter cake on the hole wall **(Belaskie et al., 1994)**. Sticking the drill string typically results in a delay in the drilling progress. An incomplete understanding of the sticking mechanism has hampered the development of preventive and remedial methods. The distribution of stuck pipe events has been investigated according to the activity level when the pipe became stuck in drilling the North Sea and the Gulf of Mexico. Stuck pipe scenarios tend to happen during drilling, tripping, back-reaming, casing running, and logging tasks **(Bradley et al., 1991)**. Understanding stuck pipe mechanisms and their classic signatures helps detect trends early and proactively deploy mitigating strategies against impending stuck incidents **(Ahmed et al., 2019)**. **Fig. 1** illustrates the most common causal drilling activities before sticking during the drilling phase of well construction **(Alshaikh et al., 2018)**. Identifying the correct category of sticking is essential to ensure proper mitigation since applying the incorrect mitigation may worsen sticking **(Spivey et al., 2019)**.

Understanding these mechanisms and the different factors involved is necessary to carry out the appropriate actions for optimal prevention. Wellbore geometry, pack-off and bridging, and differential sticking are the three main categories of stuck pipe **(Aljubran et al., 2017)**. Approximately 68-70% of stuck pipe accidents are caused by mechanical sticking, which can result from pack-off, bridging, or wellbore geometry. The remaining 30-32% of incidents are attributed to differential sticking **(Muqeem et al., 2012)**.

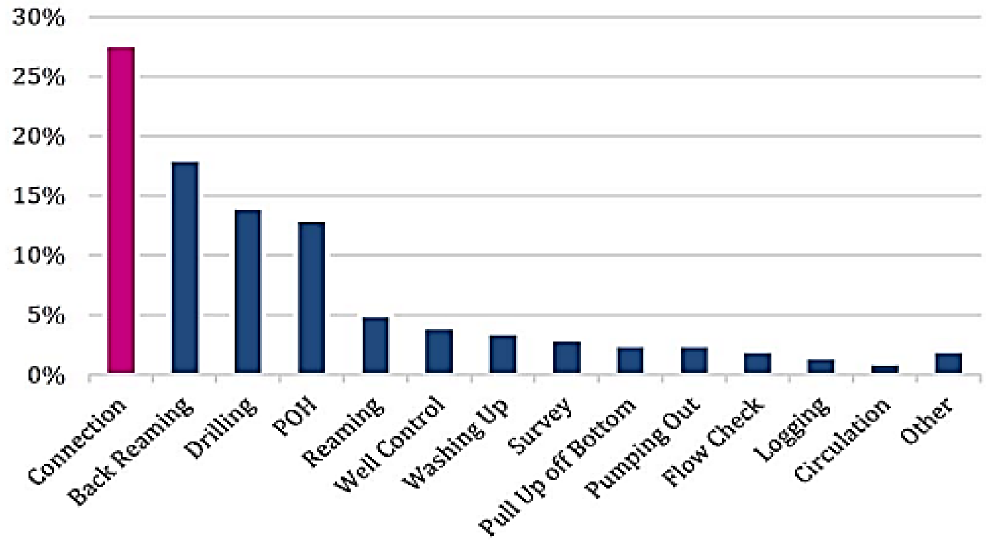


**Figure 1.** The most common activities prior to stuck pipe incidents **(Alshaikh et al., 2018)**

2.2.1 Mechanical Pipe Sticking

In general, mechanical pipe sticking occurs when the drill string is mechanically trapped downhole, meaning that there is a physical blockage in the hole that resists the movement of the pipe. A drill string may become stuck due to junk in the hole, sloughing, insufficient hole cleaning, fractured and faulted formation, reaction formation, under-gauge hole, and other factors. Pack-off, bridging, and wellbore geometry are categorized into two broad categories of mechanical pipe sticking **(Murillo et al., 2009)**. Recognizing these mechanisms and the many components involved is essential to take the necessary measures for optimal prevention.

*2.2.1.1 Packoff and Bridging*

Wellbore instability is a critical concern during drilling operations especially in the shale formations affected by both mechanical and chemical factors. it causes hole pack-off and bridging, which stop the pipe from moving and impede or stop circulation. The primary cause of hole-pack-off, or solid-induced pack-off, is inadequate cutting slip velocity. Critical signs include insufficient mud qualities, inadequate hole cleaning, and failure pumps **(Allawi, 2023)**. The mechanical factors involved the temperature of the drilling fluid, confining Pressure, the pressure inside the wellbore, and pore pressure within the rock formations which plays a significant role in wellbore stability. The type and composition of the drilling fluid (mud) critical chemical factors that affect shale wellbore stability. ultimately, a controlled penetration rate, proper hole cleaning, and adequate mud conditioning can mitigate wellbore instability related to issues during the drill **(Allawi and Al-Jawad, 2021)**. This type of sticking mechanism can occur while tripping or making a connection equally and is characterized by impossible or restricted circulation with relatively high standpipe pressure and restricted rotation and axial movement **(Aljubran et al., 2017)**.

*2.2.1.2 Wellbore Geometry*

Stuck pipe incidents can also occur due to abrupt or severe wellbore direction and configuration changes, keyseats, ledges, micro-doglegs, under gauge hole, or stiff BHA. Keyseats are the significant problems doglegs create and can be mitigated by back reaming in some cases. The BHA gets stuck at that keyseat when tripping out of the wellbore area. Doglegs are the most common cause of wellbore geometry sticking. They can result in further issues, including keyseats, ledges, or drill string failure due to high torque and side load. Several operational signs can indicate the presence of an undesired wellbore geometry downhole. For example, a keyseat causes constant T&D spikes at the tool joints while tripping out of the hole and vice versa. Sudden drag indicates when the BHA reaches high-dogleg (potential keyseat) depth. Creation Ledges resulting from interbedded hard-soft formations support the keyseat **(Aljubran et al., 2017)**.

2.2.2 Differential Sticking

Differential sticking occurs if a portion of the drill string, casing, or logging instrument gets attached to the mud filter cake and stays firmly in place because the mud pressure is higher than the pressure of the entire formation. It can only take place across permeable rock formations, such as sandstones, where a mud filter cake builds up during drilling. It does not occur in shales and other very low permeability formations where mud filter cakes normally do not form **(Reid et al., 2000)**. Differential pressure sticking is identified when the drill pipe is inflexible in rotation or vertical movement, although mud circulation remains unrestricted. While these symptoms may resemble Key Seat sticking, they often appear under various drilling scenarios **(Miri et al., 2007)**. In some areas, events related to the differentially stuck pipe can be responsible for as much as 40% of the total well cost **(Helio, 2007)**.

The mitigation for mechanical sticking may be the opposite of differential sticking, where circulating without moving the pipe can worsen differential sticking. Choosing the correct mitigation justifies the need for indicators distinguishing between these types of sticking. Differential sticking can worsen as the pipe remains static in the hole because the surface area of the pipe contacting the filter cake increases over time **(Spivey et al., 2019)**. The pressure differential influences the force required to pull the drill string through the wellbore, total contact surface area, and frictional coefficient.

*2.2.2.1 Analysis of Differential Sticking Factors*

Differential pressure sticking is undoubtedly a natural phenomenon. The severity of differential pressure sticking is influenced by several factors, including the contact area, the friction between the pipe and the mud cake, the pressure difference (overbalance) over the mud cake, and the permeable formation.

*2.2.2.2 Differential Pressure*

The pressure difference is a significant factor that contributes to differential sticking. This pressure difference must be decreased to an acceptable level to reduce the chance of differential sticking. We are unable to control the pore pressure in the reservoir. The mud density must be adjusted to control the differential pressure. When drilling into a depleted reservoir, the mud weight window wildly developed, resulting in a higher-than-expected mud weight. Adjusting the mud weight, which is the density of the drilling fluid, is necessary to control differential pressure. Differential pressure can increase the potential of invasion and forming a thick mud cake, leading to a pipe stuck. The differential pressure offered to each contact area unit induces forces that initiate the embedding of the pipe in the cake **(Issa et al., 2023)**.

*2.2.2.3 Permeable Formation*

Differential sticking occurs only in permeable rock formations, similar sandstones, where a mud filter cake builds up during drilling. It doesn't happen in shales and other shallow permeability formations where mud filter cakes often do not form **(Reid et al., 2000)**. It commonly appears in permeable or depleted formations. When the drill string is stationary, it connects a new pipe, trips, handles a drilling issue, etc. A porous and permeable formation allows filtrate invasion; thus, mud cake is dynamic on the wall

*2.2.2.4 Friction Force*

The most significant factor affected friction between the drill string and the wellbore, which led the pipe to become stuck. The friction force across the drill string is directly related to the magnitude of the overbalanced pressure, which implies the string is compressed against the wellbore wall by this pressure. Friction between a mud cake and steel varies in response to mud composition changes. Previous investigations have demonstrated a positive relationship between the friction factor and the barite content of the mud **(Isambourg et al., 1999)**. The filtrate is squeezed from the cake into the formation while the clay is left to contact the steel. The friction factor increases as the percentage of solids increases, and the sticking becomes more severe. Therefore, the rate of solids in the mud cake is a crucial characteristic to consider when designing the drilling mud **(Helio, 2007)**.

*2.2.2.5 Contact Area*

Differential sticking can worsen as the pipe remains static in the hole because the surface area of the pipe contacting the filter cake increases over time **(Spivey et al., 2019)**. Wall contact must be present for the other factors to occur in the first place. It further influences the force resulting from the differential pressure developed where the greater contact area enhances the severity of the differential force pushing on the pipe, as seen in Eq. (1)**(Mitchell, 2014)**.

$$F = \frac{1}{2} \times \mu \times A \times (P_m - P_f) \quad (1)$$

where F = differential sticking force, lbs, A = area of stuck drill string section (in$^2$), μ = coefficient of friction, $P_f$ = filtrate pressure in the filter cake, Psi, and $P_m$ = mud pressure in the wellbore, Psi

Minimizing the contact surface area between the cake and the drill collars is essential. This can be done by using a high ratio of hole-to-pipe diameters, avoiding high borehole deviation, and optimizing the BHA design. Reduce the contact area by using small, spiral, or square drill collars, stabilizers, and heavy-weight drill pipes to supplement the weight of the drill collars. The contact area between the wellbore and pipe can be decreased by reducing the thickness of the filter cake **(Miri et al., 2007)**. The best active contact area is expected with Eq. (2) **(Rabia, 2002)**.

$$A = 2h\sqrt{\left(\frac{Hs}{2} - tmc\right)^2 - \left(\frac{Hs}{2} - tmc\left(\frac{Hs-tmc}{Hs-OD_P}\right)\right)^2} \quad (2)$$

where (h) is the thickness of the permeable zone (in), $tmc$ is the thickness of the filter cake (in), $ODp$ is out the diameter of the drill pipe or drill collar(in), and $Hs$ is hole size (in).

*2.2.2.6 Mud Filter Cake*

Mud filter cake quality is critical for avoiding differential sticking, and a host of mud properties influence the filter cake quality (thickness, lubricity, and strength) **(Reid et al., 1996)**. The drilling mud's solid component will accumulate, forming a thick mud cake. This increases the chances of additional fluid loss to the reservoir, particularly in a zone where differential sticking is challenging to manage. The type and amount of solids are critical in forming a compressible, tough, low-permeability filter cake and controlling the degree of pipe sticking and pullout force required to release it. Only a thin layer is formed outside the formation by low solids drilling fluid, not a thick mud cake **(Isambourg et al., 1999)**. Reduced mud filtrate viscosities enhance the risk of differential pipe sticking. The fluid lost to formations during well drilling is associated with the development of differential sticking in permeability zones. The amount and nature of solid particles in a drilling fluid are essential for creating a flexible, compact, impermeable filter cake. Compressible cakes will compact through differential pressure increases **(Miri et al., 2007)**. A sufficient pullout force must be produced to overcome the mud cake's shear strength, which can cause mud cake failure, or the coefficient of friction between the pipe and the mud cake, which causes the pipe to move on the mud cake's surface when the pullout force is applied, to free a pipe stuck with differential sticking **(Oriji and Aire, 2020)**.

The pull force, as defined by **(Rabia, 2002)**, required to free a differentially stuck pipe is :

$$F = \Delta P \times A \times f \quad (3)$$

where $\Delta P$ is differential pressure ($Ph - Pf$) in (psi) unite, $A$ is area of contact between the pipe and the mud cake (in$^2$), and $f$ is the friction factor depending on the formation and drill collar surface it varies (0.15 -0.5). There are many parameters known to affect the stuck pipe incident, as shown in **Fig.2.**

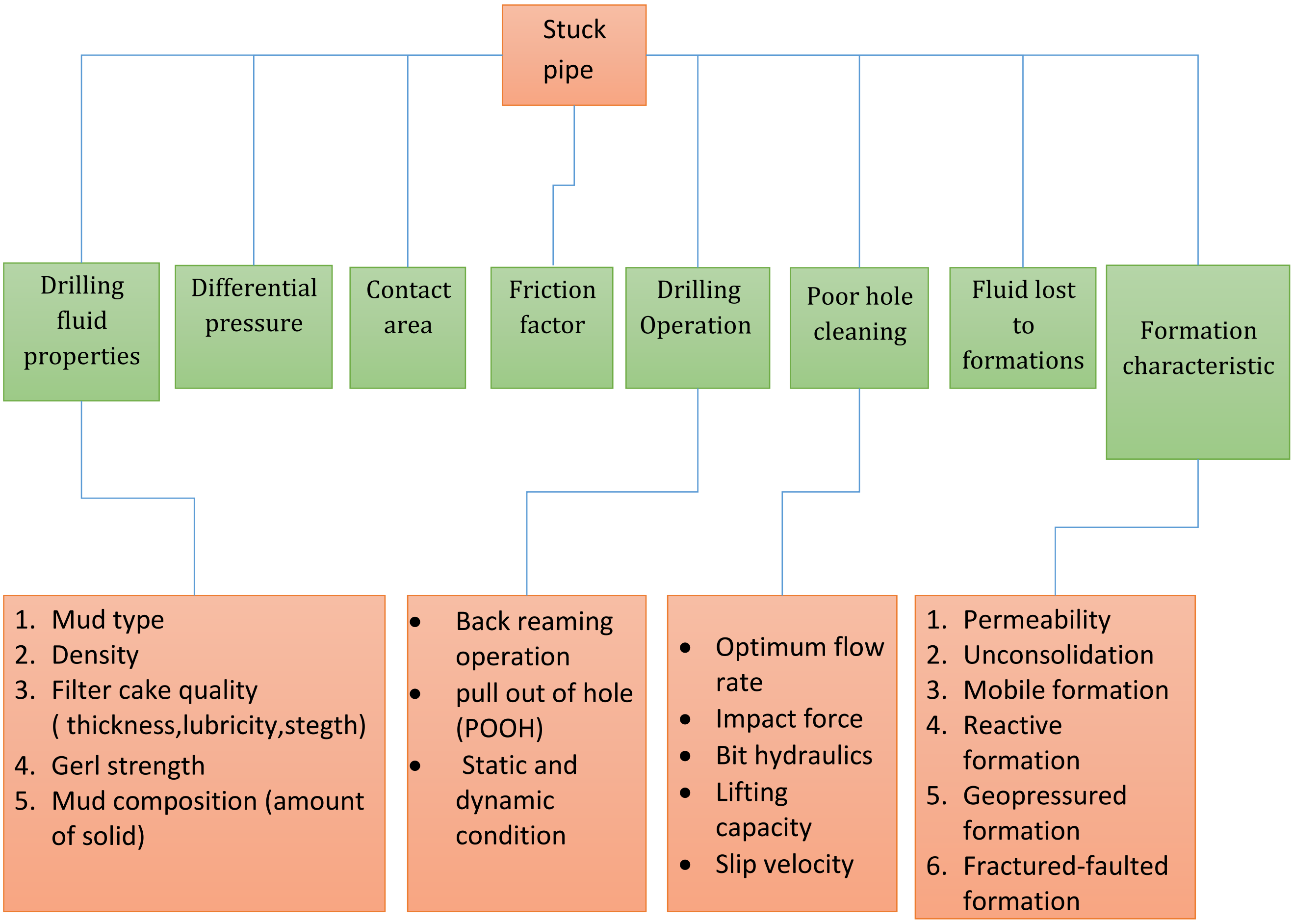


**Figure 2.** Some of the parameters known to affect the stuck pipe

2.2.3 Effect of Pore Pressure and Fracture Gradient on Stuck Pipe Management

Estimation of pore pressure and fracture gradient is very essential to minimize potential pipe-sticking problems. **(Boniface and Marcus, 2015)** stated from the results analyzed with the model, the pipe got stuck where the pressure difference between the mud hydrostatic pressure and the formation pore pressure was greater than 500 psi. A formation integrity test is usually carried out during drilling to estimate the fracture gradient. when the mud hydrostatic pressure is higher than the fracture pressure, the formation will collapse and this may lead to the stuck pipe. Maintained the mud weight drilling in the range of mud weight window that can be used to reduce the stuck pipe chance and prevent wellbore instability **(Alshaikh and Amanullah, 2018)**.

2.2.4 Effect of Drilling Mud on Stuck Pipe

Drilling mud is one of the crucial parameters of a stuck pipe. The quality of mud system design and maintenance is on top of the list of solutions to prevent stuck pipe events. The mud weight needs to be maintained to the minimum required for borehole stability and well control. Improving fluid loss can reduce the sticking tendencies of mud. Oil-based muds usually have low fluid loss values. Most collapse occurs in the mud shale Stratum due to water or drilling fluid absorbed in to make shale expansion; not good cementation conglomerate or sandstone and other strata in the drilling process, and the occurrence is more frequent **(Zhu et al., 2019)**. Also to reduce the chance of differential sticking, the time that the mud is left static in the hole should be minimized. Spotting fluids is the main remediation technique for differential sticking, especially when jarring and torqueing up are not enough to free the pipe. However, It is currently not possible to determine accurately the sticking potential of the mud from a single mud property, such as density, fluid loss, solids content, or lubricity **(Isambourg et al., 1999)**.

## 3. PREDICTION MODELS AND ANALYTICAL APPROACHES

Major companies in the industry have developed and implemented best practices for avoiding stuck pipes. Several ideas have been proposed to make stuck-pipe predictions. The potential solutions for minimizing stuck pipe incidents in drilling operations include both a drilling fluids strategy and a drilling automation technique. The drilling fluids approach focuses on optimizing drilling processes, while the drilling automation approach involves using sensors and algorithms to detect early signs of stuck pipe incidents. Both approaches aim to reduce stuck pipe incidents and improve drilling efficiency. The number of stuck pipe events has significantly decreased when appropriate remediation procedures are followed. Even with these developments, stuck pipes are still a primary source of lost time and a significant expense in drilling operations **(Yarim et al., 2007; Muqeem et al., 2012)**.

### 3.1 Analytical Methods for Predicting Pipe Sticking

Several studies in the literature include data-driven statistical analysis techniques to evaluate the probability of stuck pipe occurrences. **(Hempkins et al., 1987)** demonstrated the use of multivariate statistical analysis to predict the occurrence of stuck drill pipes based on patterns in drilling parameters. The Multivariate Discriminant Analysis (MDA) method was used by **(Howard and Glover, 1994)** to build predictive models for stuck pipe incidents in wells drilled in the Gulf of Mexico and the North Sea. The model suggests that it is a helpful tool for developing a predictive model that can categorize drilled wells into three groups: differentially stuck, mechanically stuck, and unstuck. **(Shorakaet al., 2011)** provided a multivariate statistical regression analysis model for addressing stuck drill pipe incidents in drilling wells within the Ilam and Sarvak formations of an Iranian southern oil field. Drilling data from forty (40) wells in the Ilam and Sarvak formations in Ahwaz and AbbTaymoor oil fields had to be chosen for analysis.

**(Magaji et al., 2002)** developed a new method to predict and prevent stuck pipe issues in the Niger Delta region. The stuck Pipe Risk Factor (SPRF) model is mainly utilized to estimate the potential of a pipe getting stuck to given well designs. Halliburton recently presented an application of Artificial Neural Network (ANN) tools to analyze the causes of differential stuck pipes **(Siruvuri et al., 2006)**. Feed-forward networks, Multi-Layer Perceptron (MLP), and Radial Basis Functions (RBF) were used to analyze data from 32 wells drilled in the Persian Gulf across several areas. The evaluation technique involved applying back propagation training algorithms **(Miri et al., 2007)**. The output of the claimed networks is highly dependent on input variables, including gel strength, fluid loss, mud fluid viscosity, plastic viscosity, and differential pressure. **(Murillo et al., 2009)** were the first scholars to conduct research that included two machine-learning approaches to anticipate events involving stuck pipes. They provided another soft computing method, fuzzy logic. The fuzzy model was used to predict stuck pipe occurrences and to give the

optimal values of the variables necessary to move a well from the stuck region into the non-stuck region. **(Al-Baiyat and Heinze, 2012)** applied the two most powerful machine learning techniques, i.e., artificial neural networks (ANN) and support vector machines (SVMs), to predict stuck pipe occurrences. The significant difference between these two techniques is their mathematical methodology and structure. The variations between the outputs of these tools can be obtained through accuracy measures and error calculations. Based on the findings, the investigation has demonstrated that machine learning approaches can accurately predict stuck pipe incidents with an accuracy of over 85%. The results indicated that Support Vector Machines (SVM) are more precise in predicting stuck pipe incidents than Artificial Neural Networks (ANN). ANN technique was used to develop new empirical correlations to predict the rheological properties of NaCl water-based drilling fluid in real-time correlations based on 3000 actual field measurements of mud rheological properties **(Elkatatny and Mahmoud, 2017)**.
**(Nakagawa et al., 2021)** proposed the unsupervised machine learning approach using only standard data apart from the data recorded during a stuck pipe event and several hours before pipe sticking because such data may include the signs of occurrence of the stuck pipe.

### 3.2 Comparative Analysis of Prediction Models

Some studies use surface drilling data (mud logging data) and mud properties. In contrast, others use the wellbore data in addition to the above as they are valuable data for detecting stuck pipes. However, it is challenging to obtain wellbore data with the same level of quality as that of the surface drilling data in real-time when applying the stuck prediction during the actual operation. **(Inoue et al., 2022)** conducted various approaches based on surface drilling data from multiple wells belonging to several agencies to enhance the training dataset. It also showed that supervised machine learning provides only stuck pipe detection and does not predict the stuck pipe event before the occurrence of the event. **(Zhu et al., 2019)** predicted the probability of collapse occurrence, which is obtained through computer-intelligent data analysis according to the influencing factors of collapse and sticking combined with the ground stress model of collapse. The goal is to prevent stuck drilling, increase drilling speed, and prevent insignificant waiting time. **(Ahmed et al., 2019)** developed a model for detecting early warning signs of common stuck pipe mechanisms during drilling operations utilizing a machine learning approach. The unsupervised machine learning algorithm is programmed to detect abnormalities in real-time drilling parameter trends and identify critical signatures of impending stuck pipe. **(Brankovic et al., 2020)** showed three indicators based on the mud log data to learn a statistical model that can anticipate stuck-pipe events. The preliminary results indicate that this model can provide valuable information to the drilling crew, based on which timely actions can be taken to mitigate and sometimes avoid drilling issues. **(Hakeem et al., 2021)** presented a unique approach to machine learning (ML) models based on evaluating the hook loads in the prediction curve and might provide warnings or alarms based on its trend. The models are trained to detect the described trend in a very early stage before this escalates into a stuck pipe incident. **(Belaskie et al., 1994)** implemented an innovative approach that continuously monitors friction forces and parameters throughout drill string operation, produces standardized depth profiles for assessment, and alerts the field staff and driller when sticking occurs at the Bottom Hole Assembly (BHA). **(Amin and Alhaleem,2018)** provided the graphical analysis program Easy View to create the investigation's analysis of stuck pipe incidents in the Khabaz Oil Field, and well-34 was considered for this investigation. The investigation provided recommendations for mud formulation and enhancing casing design for handling difficulties specifically to minimize risks and obstacles. **(Jardine et al., 1992)** offered a method for monitoring wellbore friction in real-time by creating depth-indexed "profiles" from surface data recorded by a computer system involving hook load and torque information. To guide the driller and other rig operators to potential issue zones during tripping and to raise their awareness of the increased risk of pipe-sticking during drilling, the model provides notification in advance of changing borehole conditions.

## 4. EXPERIMENTAL TECHNIQUES AND FIELD MEASUREMENTS

Many researchers propose experimental laboratory studies to understand how different factors, such as the composition of the mud and its properties, affect the sticking behavior. The knowledge acquired from these laboratory investigations allows an understanding of the sticking characteristics of various mud types. It permits the evaluation of a range of approaches for mitigating sticking potential. **(Courteille and Zurdo, 1985)** presented a new theoretical and experimental study of the forces involved along the pipe/cake/formation triple bond when differential pressure sticking has been established. Several types of mud have been tested and suggested new ideas for differential pressure sticking prevention. They confirmed the ability of the cake when thick to lose its permeability near the cake/pipe interface is the main reason for differential sticking. Adding calibrated solids in the mud will be helpful when differential sticking risks are present. **(Reid et al., 2000)** This study concentrated on the issue with the experimental technique used to study the phenomenon of differential sticking. A test method was demonstrated to determine the filter-cake qualities that impact the differential sticking tendency of drilling fluids. The sticking device has been utilized in multiple field tests with positive results. As the sticking value measurement indicated, the release torque increased proportionately to the static filtration time or cake thickness parameter. This parameter reflects the rate at which the cake builds up. Several efforts indicated a basic lab test to measure the fluids' ability to prevent flow into the rock to identify the risk of differential stick pipe (DSP). The test evaluates various drilling fluids by comparing their invasive characteristics within the same porous medium. It was also indicated that differential stick pipe (DSP) issues could be identified by monitoring torque and drag levels, particularly when drilling through zones with relatively low pressure **(Helio, 2007)**. Improved comprehension of differential sticking and accurate estimation of the lubricating properties of various drilling fluid systems have been noted **(Isambourg et al., 1999)**. They claimed that differential sticking forces, pull forces, and the pore pressures of mud cakes could be determined in the lab under conditions similar to the downhole. According to the consultants, the type and amount of solids influence the cake characteristics and impact the rank of pipe sticking and pullout force to get it released.

Approximately 600 wells around the Gulf Coast were analyzed to identify conditions associated with many stuck pipe events. This survey involved wells that suffered issues and those that encountered differential and mechanical issues **(Weakley, 2000)**. **(Egbe et al., 2020)** illustrate the application of a mud filter cake remover to free a differentially stuck string using an innovative enzyme/weak acid recipe to devastate the polymer base of the filter cake generated by the water-based drilling fluid. They implemented this technique in case history, and the string was freed within 1 hour of displacing the filter cake remover across the length of the string in an open hole. The string became free relatively quickly despite being differentially stuck for 29 hrs. Significant knowledge was provided on

identifying stuck pipe mechanisms and the appropriate first action to consider. Interactive teaching strategies, such as case histories, were used to increase awareness and discuss lessons acquired **(Yarim et al., 2007)**.
**(Ahmed et al., 2019)** demonstrated the sticking can easily be detected when the out-of-slips HKLD trend is tracked for RIH and POOH. Among other signals, a classic warning sign of impending differential stuck pipe is that the out-of-slips HKLD peak will continuously increase from one connection to the next during a drilling operation. The surface TRQ also similarly responds to worsening hole conditions. Increasing off-bottom rotary TRQ could also indicate growing friction in a hole due to poor hole cleaning or tight hole conditions. **(Adams, 1977)** provided an effort to calculate the limited spotting fluid quantities that can be utilized in the field to achieve the highest success ratios for affecting a pipe release. The differential pressures required to begin pipe sticking under field situations are also defined. A second strategy used in this study was to examine a modified sonic log to detect free and stuck intervals in the drill string.

## 5. CALCULATION METHODS AND SOFTWARE TOOLS

Each stuck pipe incident or occurrence must be thoroughly investigated, and its fundamental cause must be identified to understand it. Many efforts have focused on determining mathematical relationships and utilizing software to establish different models to provide optimal solutions for this incident.
The terms "soft computing," "machine learning," "intelligent machines," "data modeling," and "machine learning" pertain to computer methodologies that utilize huge amounts of learning data to acquire knowledge from previous experiences. The establishment of machine learning techniques is based on mathematical models. These models can recognize a pattern based on their comprehension of the trend or behavior of actual or experimental data **(Al-Baiyat and Heinze, 2012)**. Multiple scientific and engineering branches have recently utilized artificial intelligence to predict prevalent and significant problems. Machine learning techniques are sometimes called artificial intelligence methods since they somewhat follow and mimic human properties and abilities such as learning, generalization, memorization, and prediction. **(Shoraka et al., 2011)** developed SPSS software and discriminant analysis to construct two functions from the data of a three-day drilling operation, which were used to predict the drilling situation the following day by analyzing cross plots. **(Oriji and Aire, 2020)** illustrated using the software (SP analyze) to diagnose stuck pipe mechanisms quickly and reduce losses resulting from downtime.
The implementation process is summarized using flow charts for the numerous diagnosis programs. **(Al-Baiyat and Heinze, 2012)** demonstrated a combined model of the most powerful machine learning (ML) consisting of ANN and SVM, which is shown to predict stuck pipe occurrences. The algorithms of these models were written utilizing MATLAB language. The MATLAB software has a built-in neural network model to classify the data into two or more classes.

## 6. RESEARCH CHALLENGES AND FUTURE DIRECTIONS

Stuck pipe incidents pose significant challenges in the drilling industry, impacting cost, time, and overall efficiency. Predicting a stuck pipe is perhaps one of the most complex problems in the drilling industry, not only because of the complexity of the natural factors involved, such as formation and variation of pore pressures but also due to the complexity of the drilling operation itself, which is continuously influenced by the rig crew activities and decisions for proactive freeing mechanisms. Effective stuck pipe prediction becomes more challenging and requires real-time advanced analysis of all available drilling data **(Malki et al., 2023)**. Acquiring comprehensive and high-quality data remains a challenge. Developing an accurate predictive model, particularly for machine learning models that rely on database size, requires more relevant stuck pipe parameters and higher model accuracy. In the future, collaborative efforts between researchers, industry professionals, and technology providers will drive innovation in stuck pipe prevention and management. Addressing these challenges can enhance drilling safety, reduce costs, and improve operational efficiency.

## 7. ANALYSIS AND DISCUSSION

This study showed the successful use of surface parameters, Physical Model computations, and Machine Learning methods to identify stuck pipes, a significant cause of Non-Productive Time (NPT) in drilling operations. The best solution to a stuck pipe is to recognize the environments in which it is likely to occur and avoid them. The results of more studies showed that (SVM) is more accurate in stuck pipe prediction than ANNs. Besides, it can be found that SVM is more convenient than ANNs since they need fewer parameters to be optimized. Regression analysis can be applied accurately for any well categorized as stuck or non-stuck. Discriminant analysis is better than regression analysis in the predicted stuck pipe before it occurs with a more extended period to make the correct action. Sensitivity analysis of data for various fields assists in determining the parameters that significantly increase the risk of differential pipe sticking. Predicting potential stuck conditions can be very effective during drilling, with an accuracy of more than 90% in some studies, using the available real-time data feed of various operational parameters. After the stuck pipe accident, the corresponding parameter changes are the reference basis for the occurrence of the stuck pipe accident. Wellbore inclination, rate of penetration, lithology type, and BHA length have a more significant effect on stuck pipe occurrence. All the signs that the well can provide, such as difficulty tripping in/out of the hole or slow penetration attributed to the difficulty in applying proper weight on the bit, should be seen with caution because they can signal an increase in drilling stuck pipe risks. A comparison of generic mud types has shown oil-based muds to have the lowest sticking values and gel-water-based mud has the highest. Polymer-water-based muds fall between these two extremes. It was found that the sticking potential also varies greatly within a mud type, depending on the precise formulation tested. Stuck pipe expenses have decreased by more than 70% due to the efforts of the task force approach that demonstrated the causes behind this issue. ExxonMobil development company experienced only three differential sticking events out of 3,446 wells drilled from 2004 through 2008 using recommended standard practices birthed out of a successful initiative. It is also noted that an additional 17 sticking events occurred when drilling did not conform to recommended practices. Out of the 17 events, 14 of these were freed. **Table 2.** summarizes the stuck pipe issue studied and the solution proposed and implemented by researchers.

**Table 2.** Stuck pipe problems that were studied and solutions used by researchers

| | Researchers | Field | Solution, technique, or model |
|---|---|---|---|
| Stuck pipe events | **(Adams, 1977)** | field cases | Analysis and discovery of fluid applications. Analyzing the modified audio recording to detect intervals of stuckness. Considering composition characteristics such as water content for pipe adhesion tendencies. The identification of formation pressure regimes involved in pipe adhesion. |
| | **(Helio, 2007)** | field cases | Laboratory test to Evaluate the non-invasive effectiveness of drilling fluids. Three drilling fluids have been tested. the fluid composition tested claimed to be non-invasive, with a significant amount of bridging agent. Suggests that the ultra-low solids fluids can reduce the risks of stuck pipe. |
| | **(Amin and Alhaleem, 2018)** | Khabbaz | Use Easy View software to analyze stuck pipe causes. Selecting the appropriate type of drilling fluid. Optimize casing seat design to reduce stuck pipe probability. Recommendations for drilling fluid rheology properties and casing seat design. |
| | **(D'Amicis et al., 2023)** | field cases | The hidden Markov Model (HMM) produces different alarm levels with 60% of the stickings predicted. Utilize mudlog data to design detectors for precursor events. The model is only time-based and does not consider tripping phase information. |
| | **(Nezhad et al., 2012)** | Maroon | Utilize neural networks to predict drill string sticking efficiently. Implement feed forward and back propagation network training methods. Results suggest neural networks are effective. |
| | **(Eren et al., 2013)** | Southern Fields in Iraq. | Analyzing the stuck pipe events encountered during the development drilling campaign. Monitor drilling fluid properties closely to prevent excessive filter cake. Determine the loss zone accurately for mitigation action. Training, crew awareness, and good planning prevent stuck pipe occurrences. |

## 8. CONCLUSION

This article provides an important principle for researchers to consider when reducing pipe-sticking issues.

- Artificial intelligence enhances drilling decision-making by employing knowledge of downhole drilling conditions to improve accuracy. It replaces the potential for human error in applying control variables such as WOB, RPM, mud rheology, and rig settings.
- Differential pipe sticking is one of the stuck pipe mechanisms that have significantly impacted drilling efficiency and well costs. In some areas, events related to differentially stuck pipes can be responsible for as much as 40% of the total well cost.
- The observed anomalies in the stuck pipe models may not necessarily indicate stuck pipe events but other issues, such as circulation loss or downhole equipment failure. Allows the model to be combined with different models to identify additional drilling problems and develop a drilling guiding system that operates in real time.
- When moving the string and circulating the hole clean, the speed must be controlled to avoid specifically fracturing or unstabilizing the shale layers. It is recommended to raise and lower the drill string at ±5 min/stand and ±2 min/stand, respectively.

- The huge amount of data produced while drilling holds valuable information and, when effectively used by an Artificial Intelligence (AI) model, can prevent NPT, such as stuck pipe events.
- The supervised machine learning constructs only stuck pipe detection and does not anticipate the stuck pipe event before the occurrence of the event. An unsupervised machine learning algorithm develops a trained model that outputs a value equivalent to the stuck pipe risk by comparing the predicted value with the observed value.
- The composition of spotting fluids varies based on the formation and drilling of mud, and the success of this technique is related to the volume of fluid used.
- A review of published literature and laboratory data has established the importance of a sticking device (Stickance tester), which effectively detects the sticking potential of mud and establishes mud formulation and engineering guidelines to reduce the risk of differential sticking.

## NOMENCLATURE

| Symbol | Description | Symbol | Description |
|---|---|---|---|
| A | Area of stuck drill string section, in$^2$. | NPT | Non-productive time |
| AI | Artificial intelligence | $ODp$ | Out the diameter of the drill collar(in) |
| ANN | Artificial neural networks | Pm | Mud pressure in the wellbore, psi |
| DSP | Differential stick pipe | $Ph$ | Hydrostatic pressure, psi |
| F | Differential sticking force, lbs | $Pf$ | Formation pressure, psi |
| $f$ | Friction factor | SVM | Support vector machine |
| h | Thickness of the permeable zone, in. | $tmc$ | Thickness of the filter cake (in) |
| $Hs$ | Hole size (in) | µ | Friction coefficient |
| MDA | Multivariate discriminant analysis | $\Delta P$ | Differential pressure ($Ph - Pf$), psi |
| ML | Machine learning | | |

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## Credit Authorship Contribution Statement

Amel Habeeb Assi: Writing, review, and editing. Proof-reading version, and methodology
Ahmed Taqi Kahdim Mahmood: Writing of original draft, and methodology.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# مراجعة شاملة لآلية استعصاء الأنابيب في عمليات حفر آبار النفط

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**الخلاصة**

نظرًا لأن الأنابيب العالقة تعتبر مساهمًا رئيسيًا في الوقت غير الإنتاجي (NPT) في عمليات صناعة الحفر، فلا يمكن المبالغة في التأكيد على الجهود المبذولة للحد من حدوثها تاريخياً، تبين أن أحداث الأنابيب العالقة تكلف الصناعة النفطية مئات الملايين من الدولارات سنويًا وأكثر من 25% من الوقت غير الإنتاجي. تتجاوز تكاليف الأنابيب المتوقفة لدى شركة البترول البريطانية 30$ مليون دولار سنويًا. تقدر تكاليف الأنابيب العالقة في الصناعة النفطية بأكثر من 250$ مليون دولار سنويًا. إحدى الإستراتيجيات لتجنب مشكلات الأنابيب العالقة هي التنبؤ باستخدام بيانات الحفر المتاحة، والتي يمكن استخدامها لضبط متغيرات الحفر. تم استخدام أسلوب التعلم الآلي (ML) لتحديد إشارات التحذير وتوقع أحداث الأنابيب المتوقفة نظرًا لقدرته على التعامل مع علاقة المتغيرات المعقدة. تقترح هذه المقالة مراجعة شاملة للتحديات المرتبطة بقضايا التصاق الأنابيب للكشف عن العلامات التحذيرية والمؤشرات المبكرة للأنابيب العالقة أثناء الحفر لمنعها وتقديم توصيات تشغيلية لتجنب أو تحرير الأنابيب العالقة. وأخيرًا فان هذه الورقة البحثية تحلل وترسخ فكرة أهمية أساليب الذكاء الاصطناعي للتنبؤ بحالة الأنابيب العالقة أثناء حفر الآبار.

**الكلمات المفتاحية:** الأنابيب المستعصية، التعلم الآلي، الالتصاق التفاضلي، الوقت غير الإنتاج (NPT) .